What Have We Learned from Electron Deep Inelastic Scattering?

Xiaochao Zheng
Univ. of Virginia
October 31, 2011

- Introduction – the four interactions, the Standard Model, and the role of electron scattering

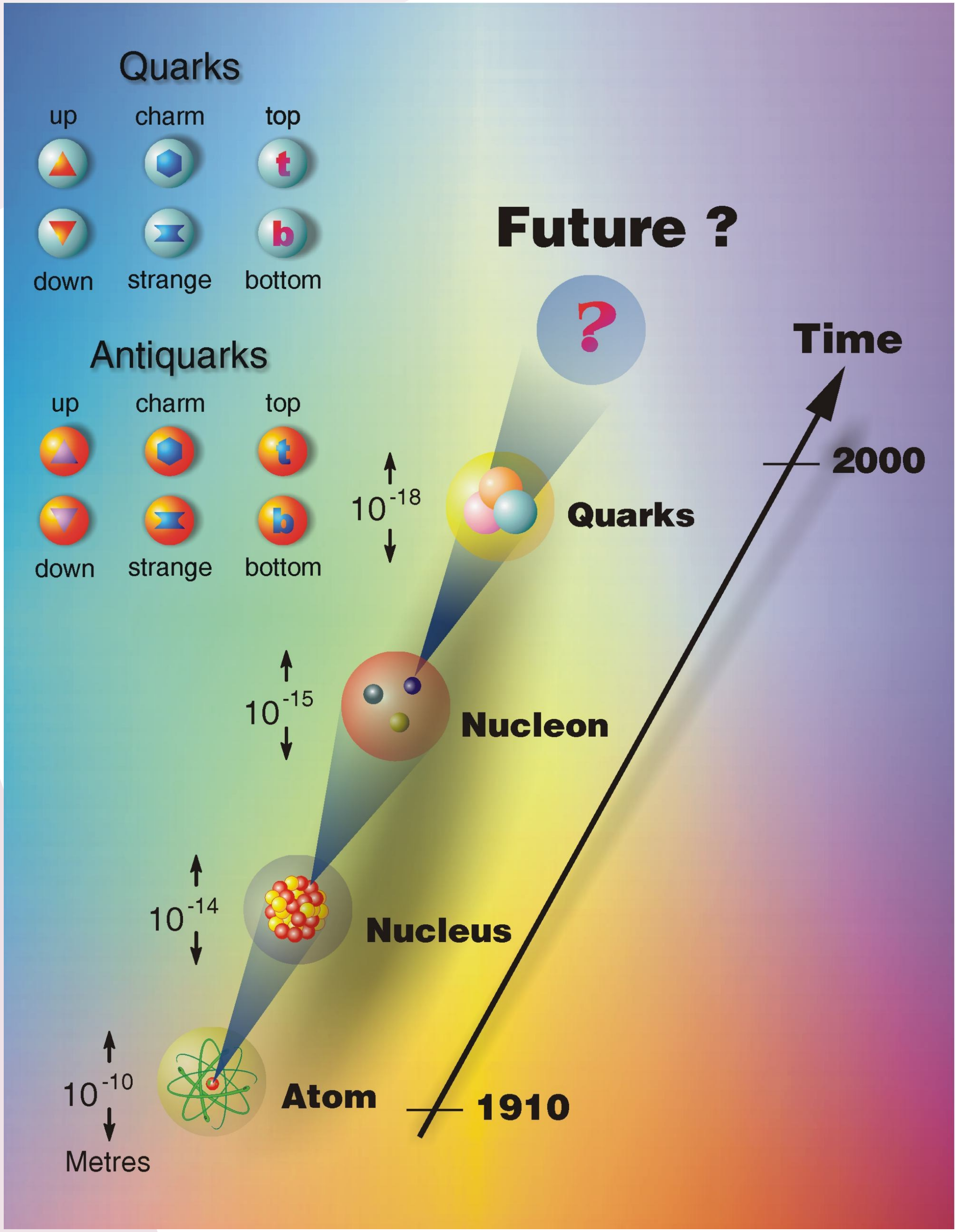
How is the nucleon energy shared among quarks?

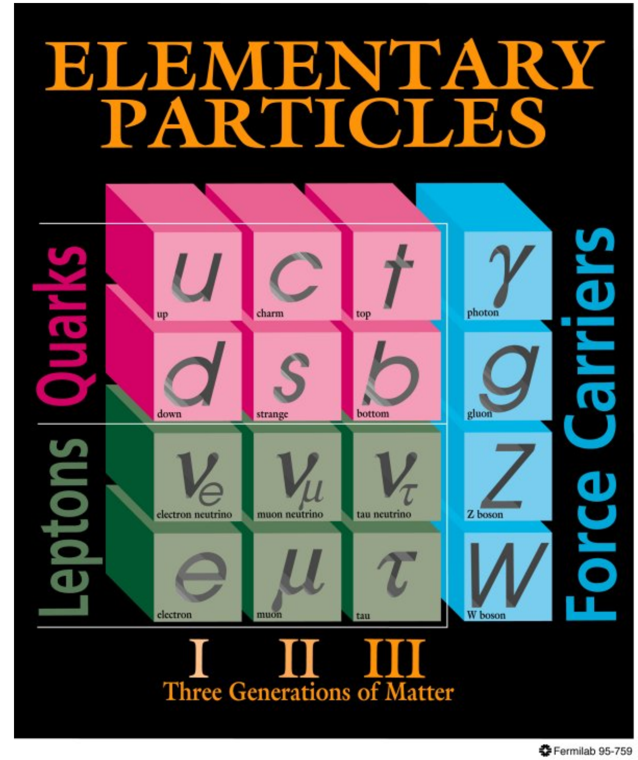
How are quarks polarized inside the nucleon?

How do quarks behave in neutral weak interactions?

- Summary

What Is the World Made of?





Mass of the nucleon: 1 GeV

~ 10^{-10} Joules

~ $(5\times10^{-15}\text{m})^{-1}$ = $(5 \text{ fm})^{-1}$

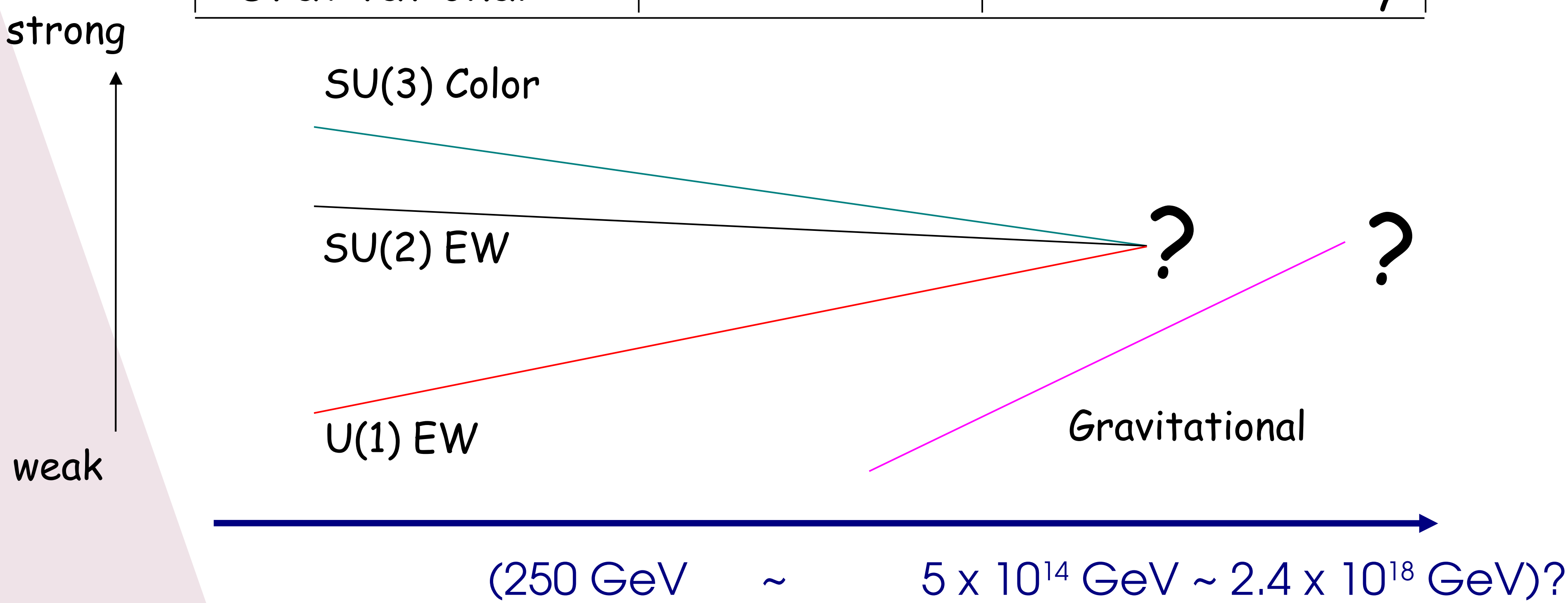
~ $(10^{-24}$ seconds$)^{-1}$

~ 10^{-24} grams,

(10^{-35} of Empire State Building)

And How Do They Interact?

Electromagnetic	10^{-2}	SU(2)xU(1)
Weak	10^{-5} at low E	group theory
Strong	10^{-1}~10^{0}	SU(3) QCD
Gravitational	10^{-38}	General relativity

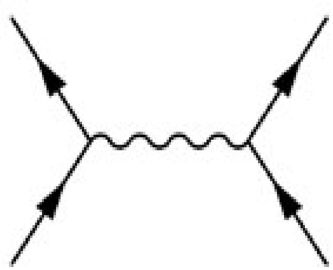


And How Do They Interact?

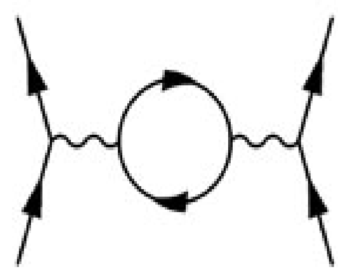
Electromagnetic	10^{-2}	SU(2)xU(1) group theory
Weak	10^{-5} at low E	
Strong	10^{-1}~10^{0}	SU(3) QCD
Gravitational	10^{-38}	General relativity

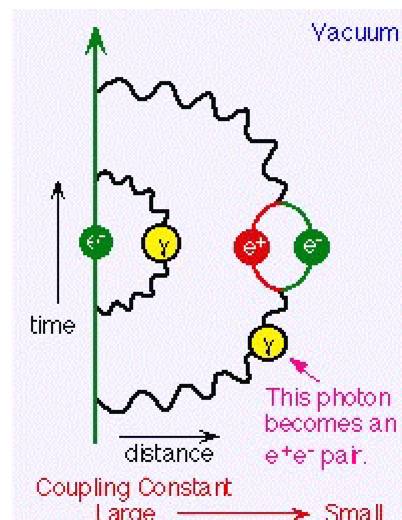
Electromagnetic Interaction – Interaction of electric charge (QED)

- Carried by photons: massless, spin-1, electrically neutral
- Well understood, higher order processes correctable, tested to 10^{-9} accuracy



vs.





And How Do They Interact?

Electromagnetic	10^{-2}	SU(2)xU(1)
Weak	10^{-5} at low E	group theory
Strong	10^{-1}~10^{0}	SU(3) QCD
Gravitational	10^{-38}	General relativity

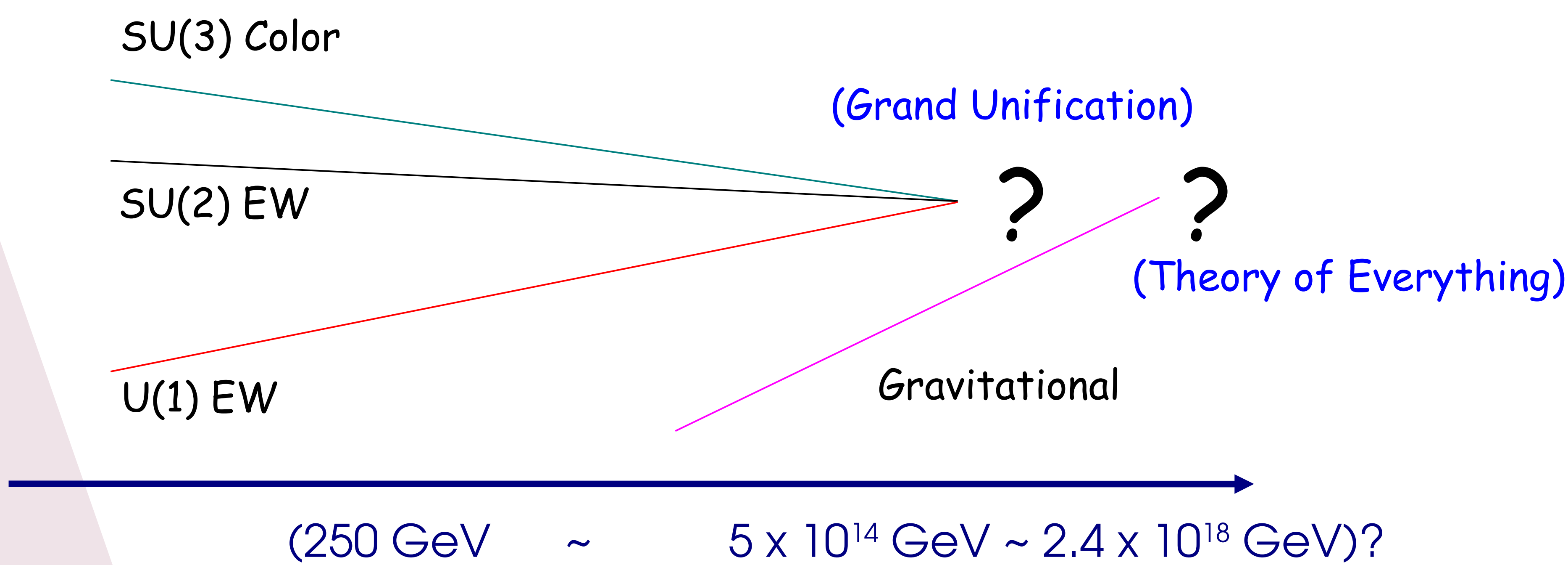
Weak Interaction – Interaction of Weak Charges

- Massive spin-1 bosons Z^0, $W^{\pm}$; Appears to be weak at low energies;
- Unified with electromagnetic interaction via the "mixing" of SU(2)xU(1);
- Violates parity symmetry;
- Tested to good precision, but is challenged by experiments (neutrino oscillations, etc.)

And How Do They Interact?

Electromagnetic	10^{-2}	SU(2)xU(1)
Weak	10^{-5} at low E	group theory
Strong	$10^{-1}\sim 10^{0}$	SU(3) QCD
Gravitational	10^{-38}	General relativity

Weak Interaction – Interaction of Weak Charges



And How Do They Interact?

Electromagnetic	10^{-2}	SU(2)xU(1) group theory
Weak	10^{-5} at low E	
Strong	10^{-1}~10^{0}	SU(3) QCD
Gravitational	10^{-38}	General relativity

Weak Interaction – Interaction of Weak Charges

Indirect search for (signs of) Beyond the Standard Model Physics, such as tiny changes in interaction strengths,

eV-GeV

SU(3) Color

SU(2) EW

U(1) EW

Gravitational

Direct search (LHC...) 7 TeV

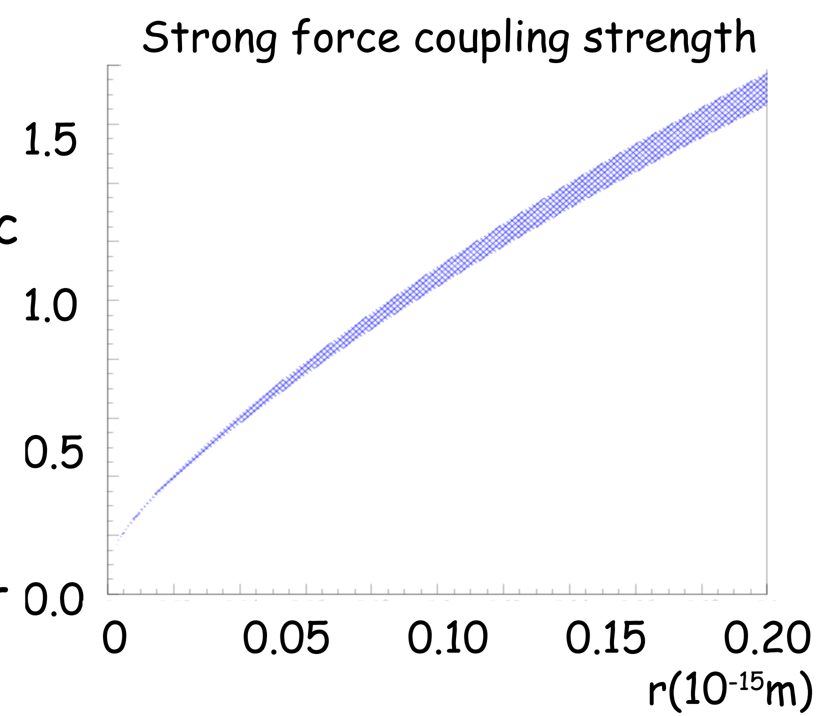
(250 GeV ~ 5×10^{14} GeV ~ 2.4×10^{18} GeV)?

And How Do They Interact?

Electromagnetic	10^{-2}	SU(2)xU(1)
Weak	10^{-5} at low E	group theory
Strong	$10^{-1}\sim10^{0}$	SU(3) QCD
Gravitational	10^{-38}	General relativity

Strong Interaction – Interaction of 3 Color Charges (QCD)

- Gluons: massless, spin-1, but carries colors
- Higher order processes gives:
  - small couplings at high energies (asymptotic freedom, perturbative QCD)
  - large couplings α_s>1 at long distances (>0.1fm), calculation very difficult
- Colored objects do NOT exist in Nature – experiments with free quarks and gluons not possible; Color confinement cannot be computed in QCD (yet).



The Role of Electron-Nucleon Scattering

Electromagnetic	10^{-2}	SU(2)xU(1)
Weak	10^{-5} at low E	group theory
Strong	10^{-1}~10^{0}	SU(3) QCD
Gravitational	10^{-38}	General relativity

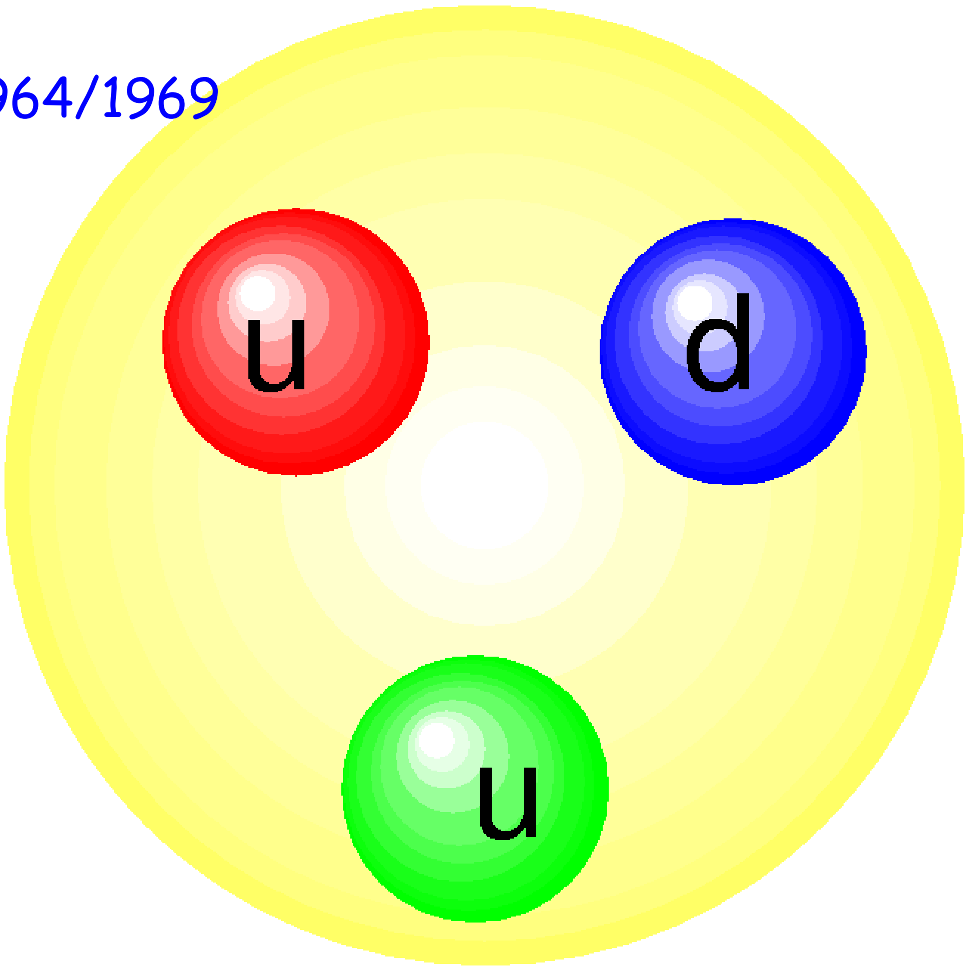
Electron beam = a source of photons and Z^0's

- γ's: probe structure of the nucleon – how do quarks form the nucleon energy, mass, spin … … via strong interactions?
- Z's: parity violation electron scattering

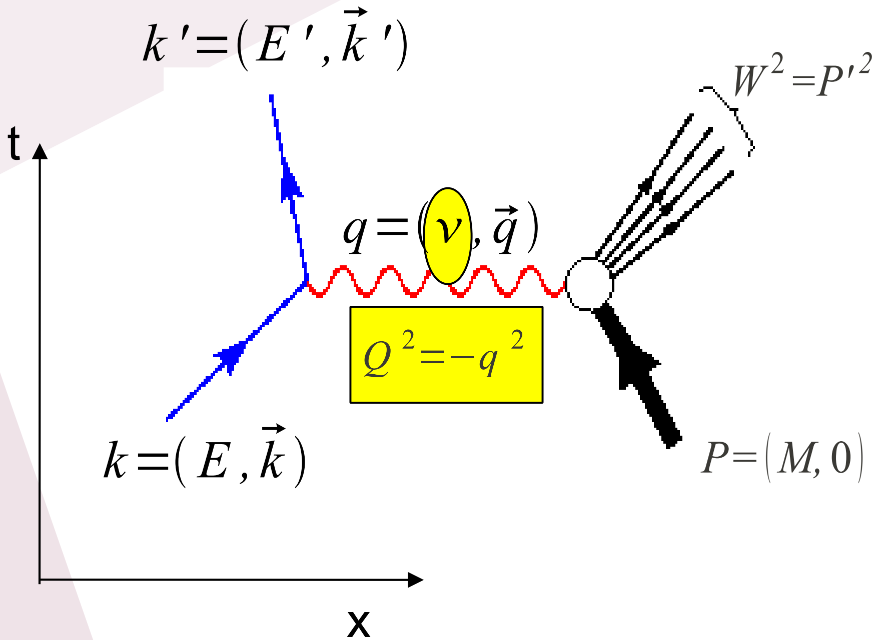
What is the Nucleon Made of?

The simple quark model of hadrons

Gell-Mann (Nishijima) 1961-1964/1969



Exploring Nucleon Structure Using Electron Scattering

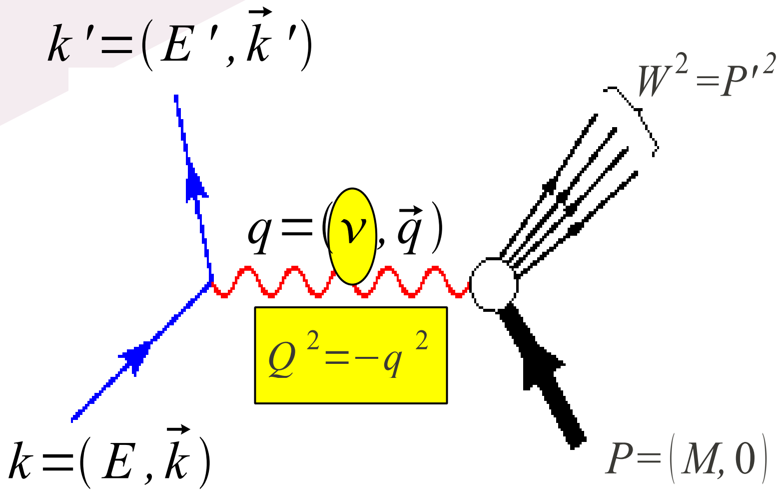


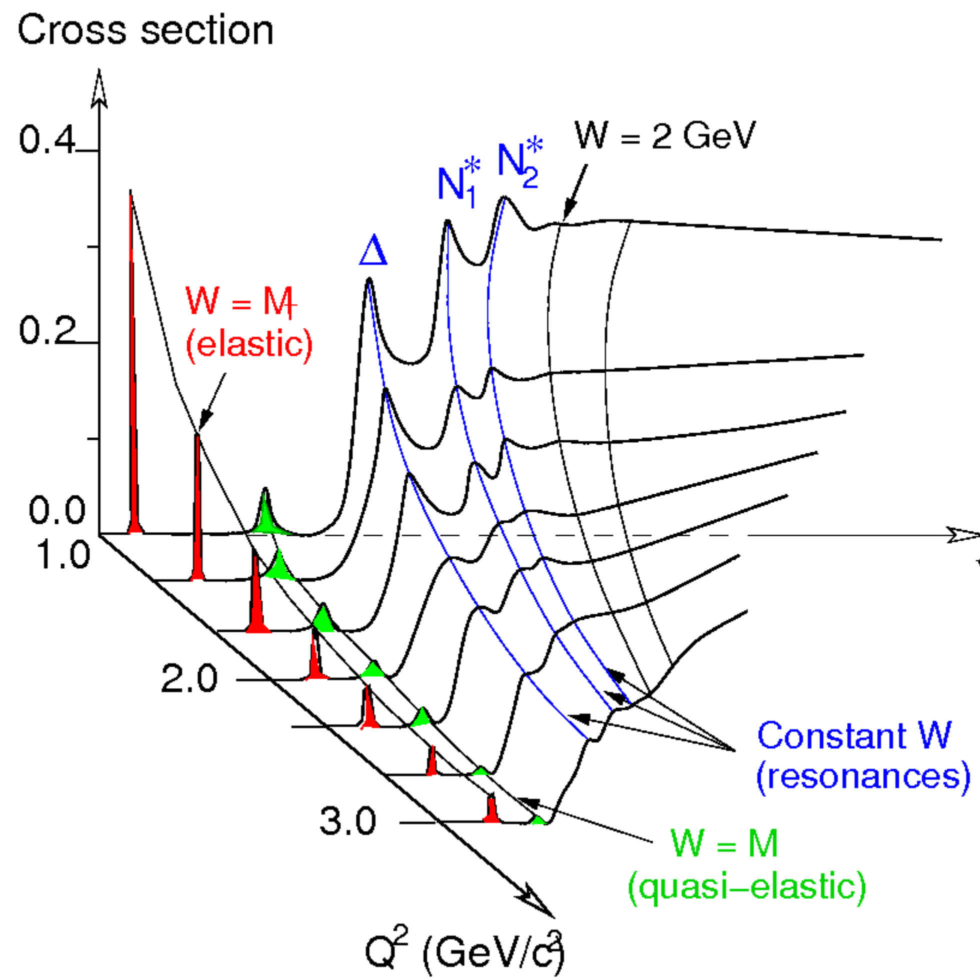
- The inclusive scattering "cross section" describes the probability of electrons being scattered to E' and Ω.

$$\frac{d^2\sigma}{d\Omega\, dE'}=\sigma_{Mott}\left[\alpha F_1\left(Q^2,\nu\right)+\beta F_2\left(Q^2,\nu\right)\right]$$

For point-like target

Exploring Nucleon Structure Using Electron Scattering

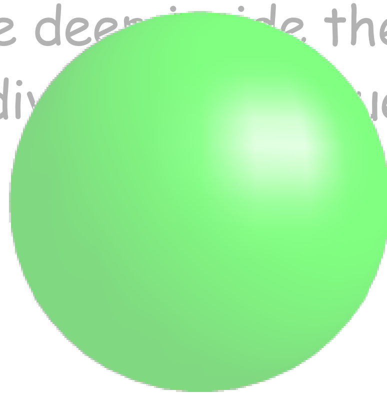


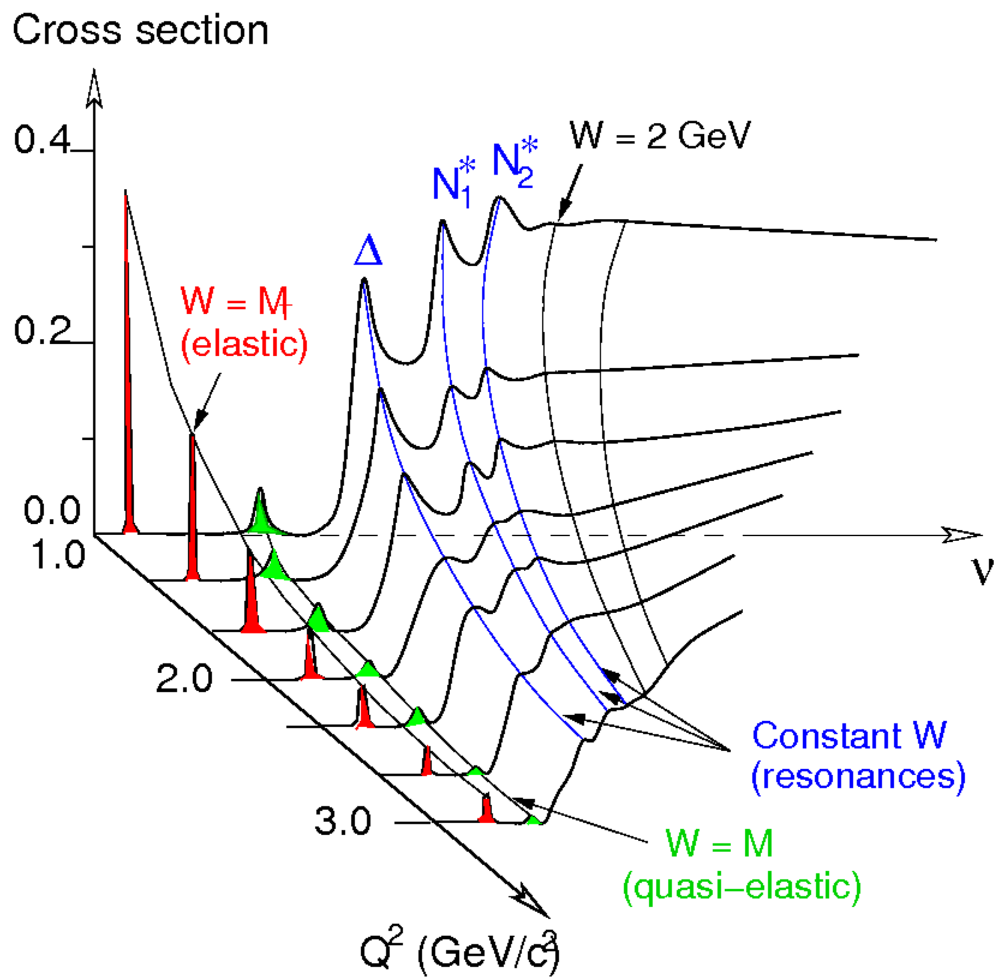


Exploring Nucleon Structure Using Electron Scattering

Elastic, quasi-elastic, resonances, deep inelastic

- ➔ (Quasi-) elastic – the nucleus (nucleon) appears as a rigid body
- ➔ Resonance region – quarks inside the nucleon excited to resonance modes
- ➔ Deep Inelastic Scattering (DIS):
  - start to see dee[illegible]de the nucleon (indiv[illegible]uents)



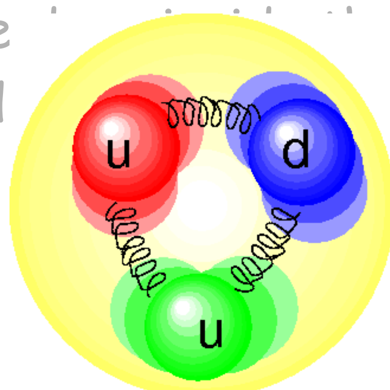


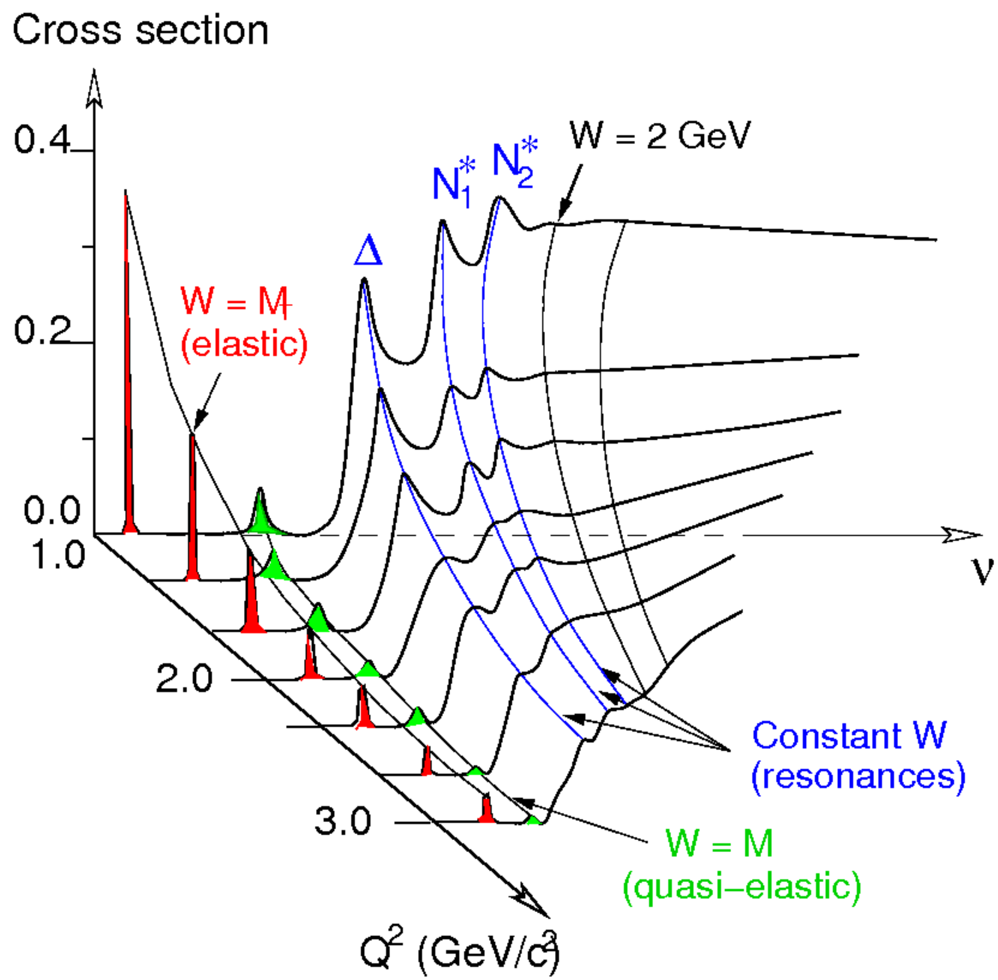
(highly non-pertubative, phenomenology models)

Exploring Nucleon Structure Using Electron Scattering

Elastic, quasi-elastic, **resonances**, deep inelastic

- (Quasi-) elastic – the nucleus (nucleon) appears as a rigid body
- **Resonance region – quarks inside the nucleon excited to resonance modes**
- Deep Inelastic Scattering (DIS):
  - start to see … nucleon (ind… …nts)



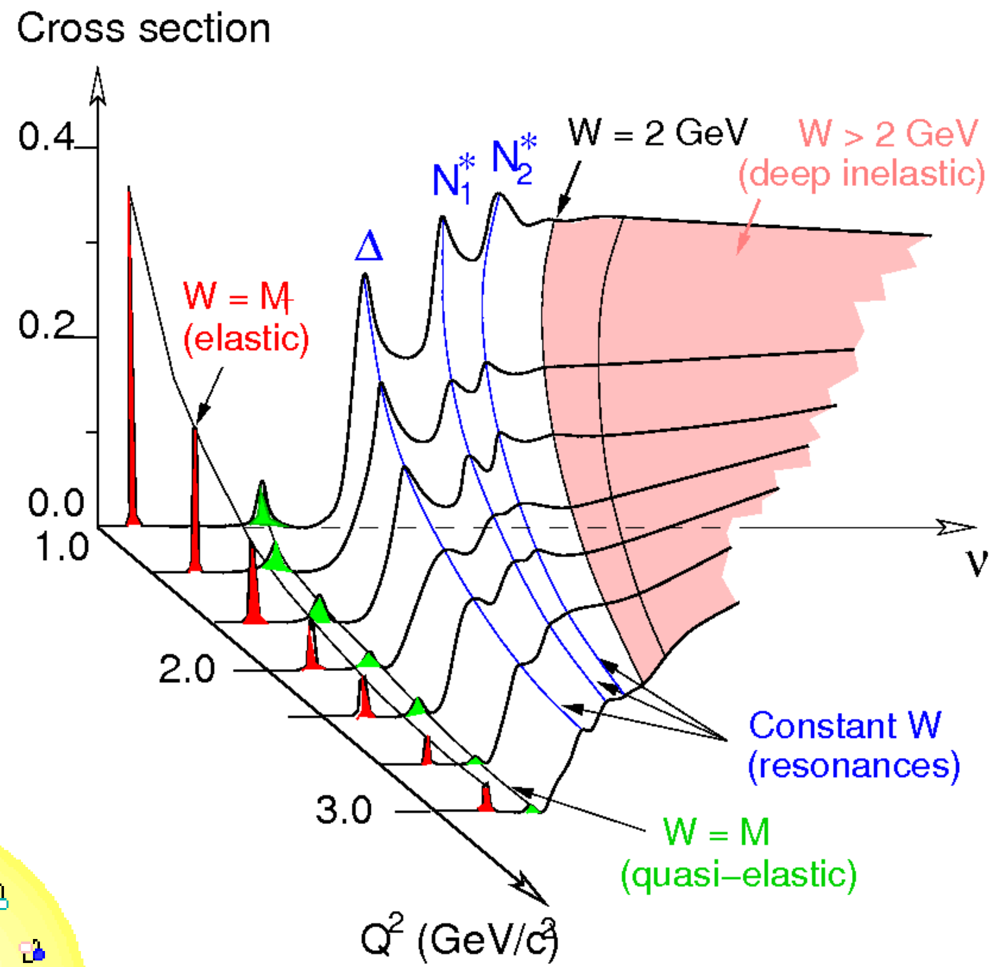


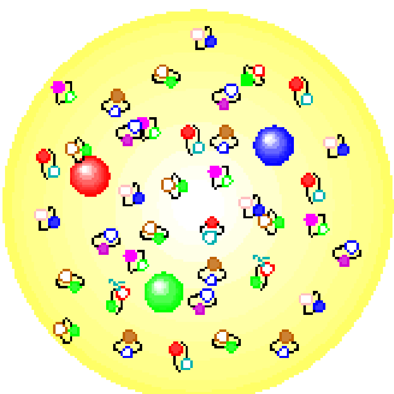
(highly non-pertubative, phenomenology models)

Exploring Nucleon Structure Using Electron Scattering

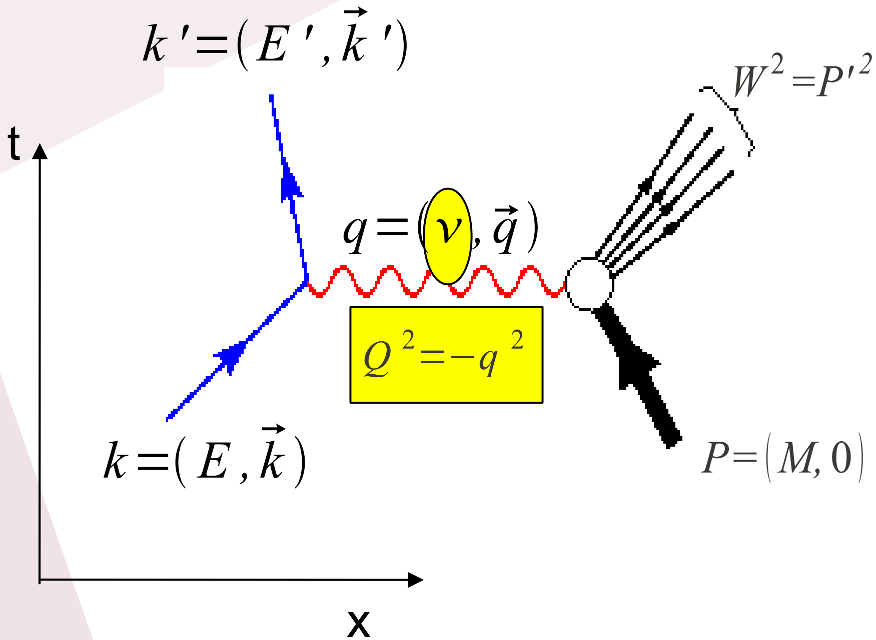
Elastic, quasi-elastic, resonances, deep inelastic

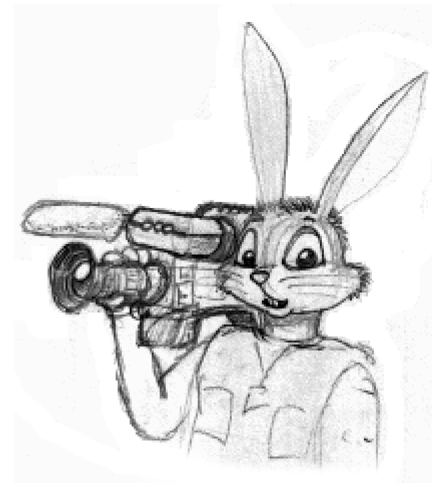
- (Quasi-) elastic – the nucleus (nucleon) appears as a rigid body
- Resonance region – quarks inside the nucleon excited to resonance modes
- Deep Inelastic Scattering (DIS):
  - Start to see deep inside the nucleon (individual constituents)





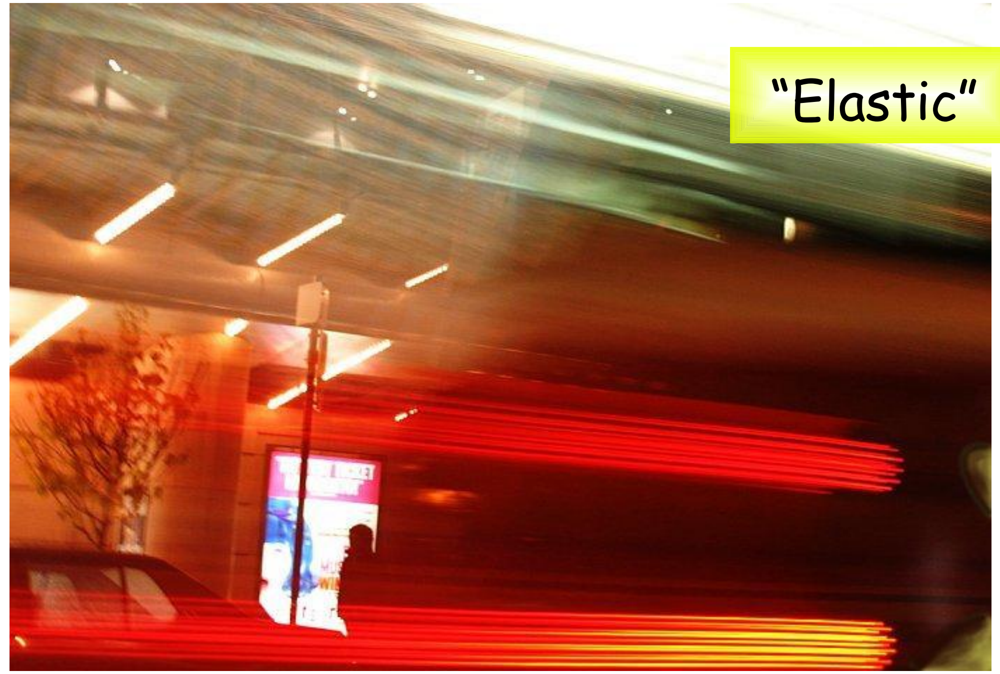
Virtual photon compared to (real, visible) photon

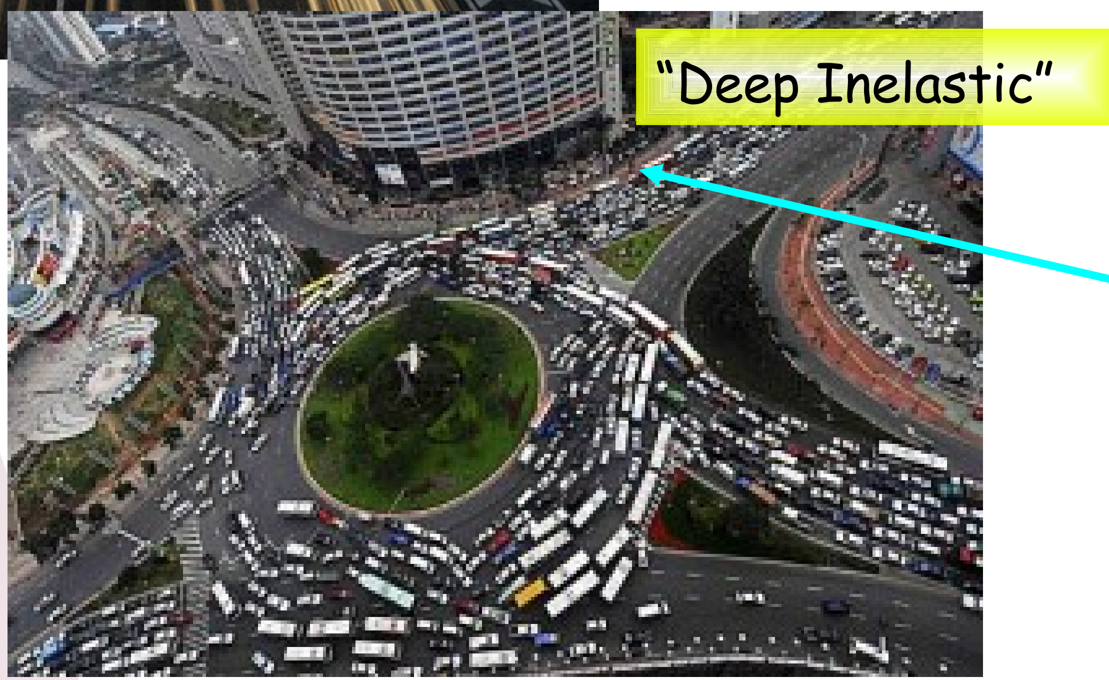




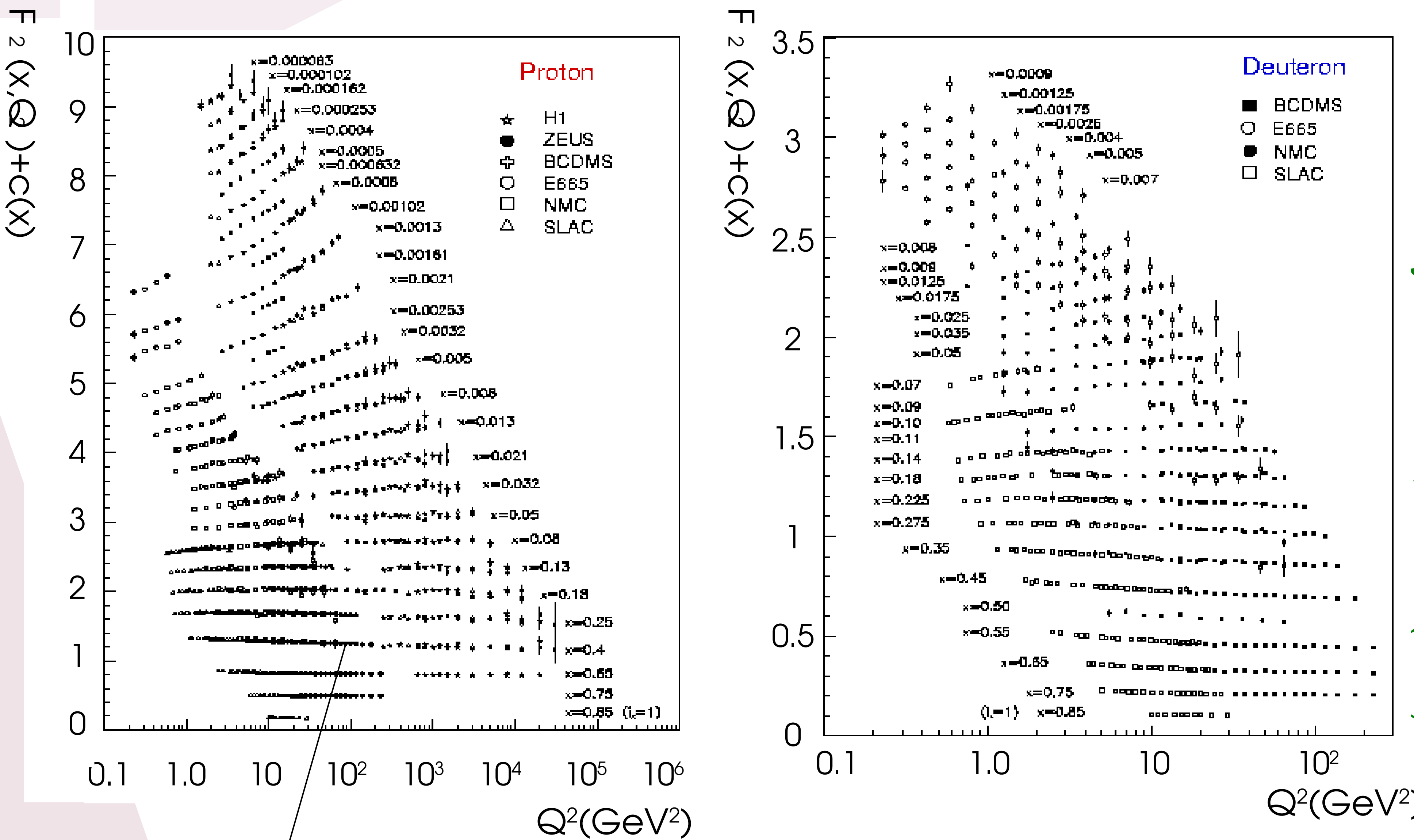
- Focus (spatial resolution): $1/Q^2$
- Time exposure $1/\nu$


“Resonance”


“Elastic”


“Deep Inelastic”

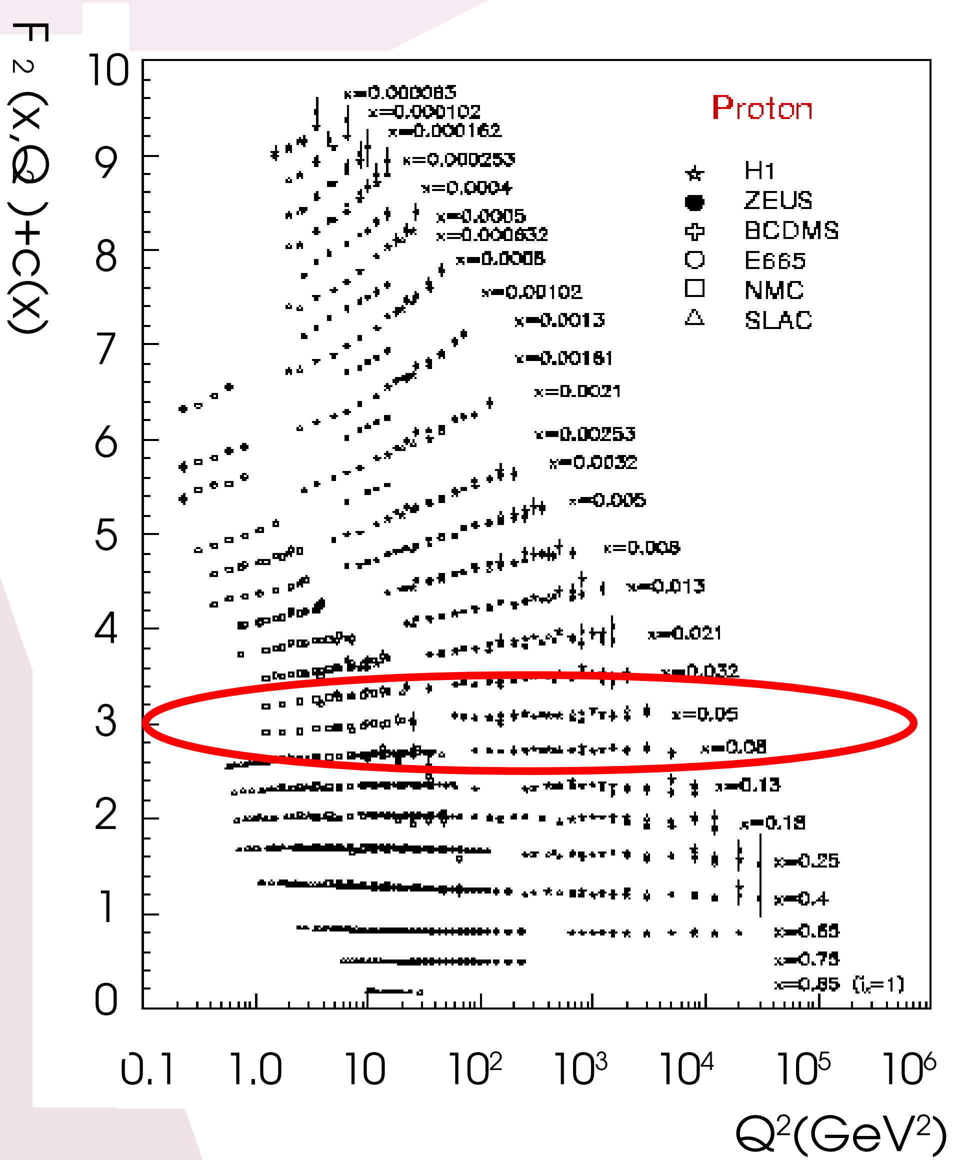
From Electron Deep Inelastic Scattering



Phys. Rev. D 66, 010001 (2002)

shifted according to Q^2/ν

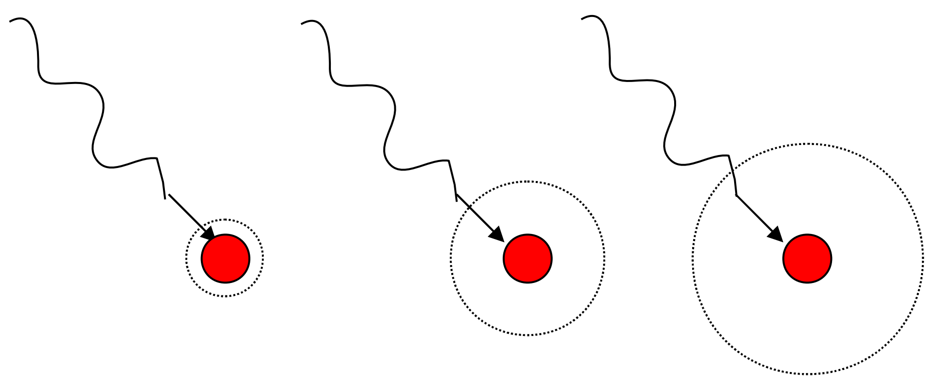
From Electron Deep Inelastic Scattering



"scaling":

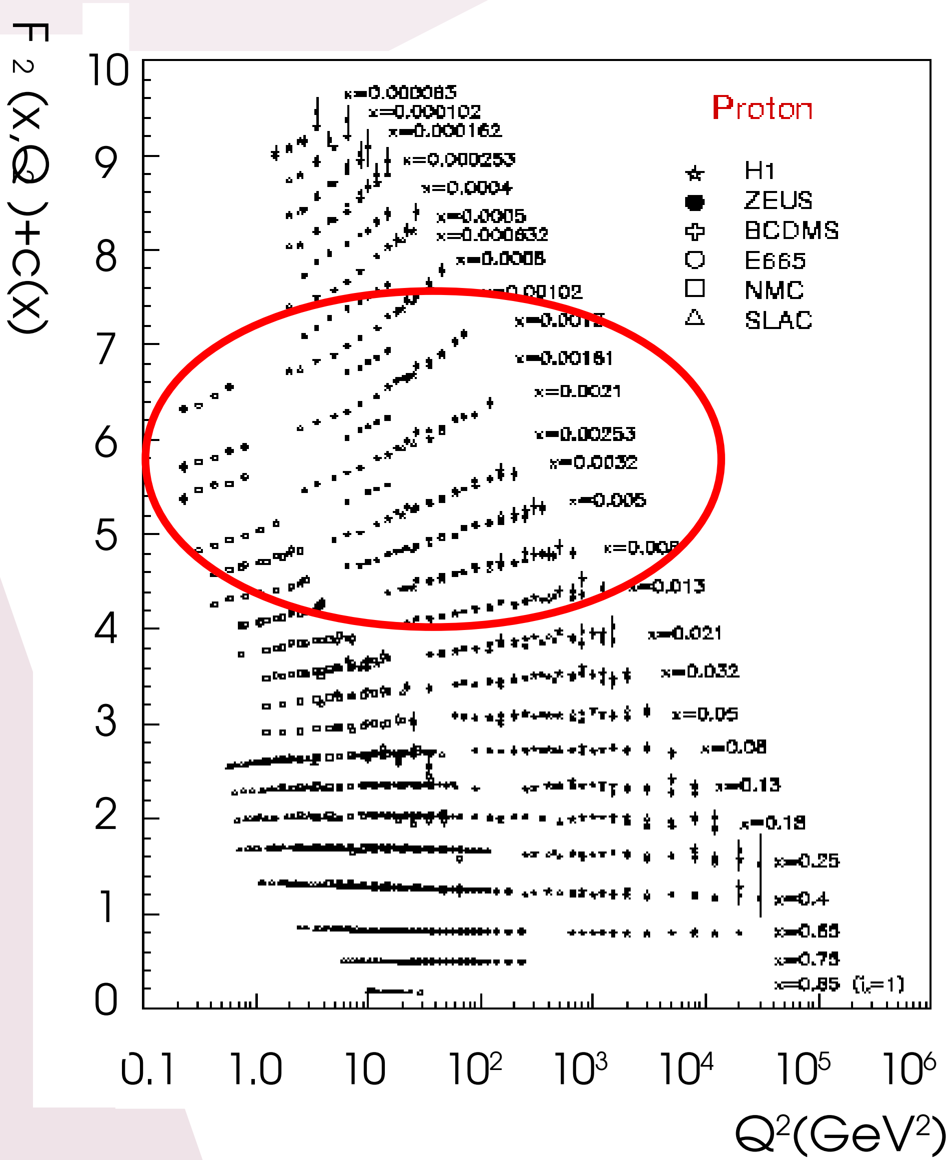
What we observe is independent of the resolution of the photon probe ($1/Q^2$)

the constituents must be point-like particles, spaced far apart.



Friedman, Kendall, Taylor et al. 1968/1990

From Electron Deep Inelastic Scattering



"scaling violation"

$\text{Log}(Q^2)$ dependence

the quarks are weakly interacting inside the nucleon

"Asymptotic Freedom"

$$\alpha_S(Q^2)=\frac{4\pi}{(11-2n_f/3)\ln(Q^2/\Lambda^2)}$$

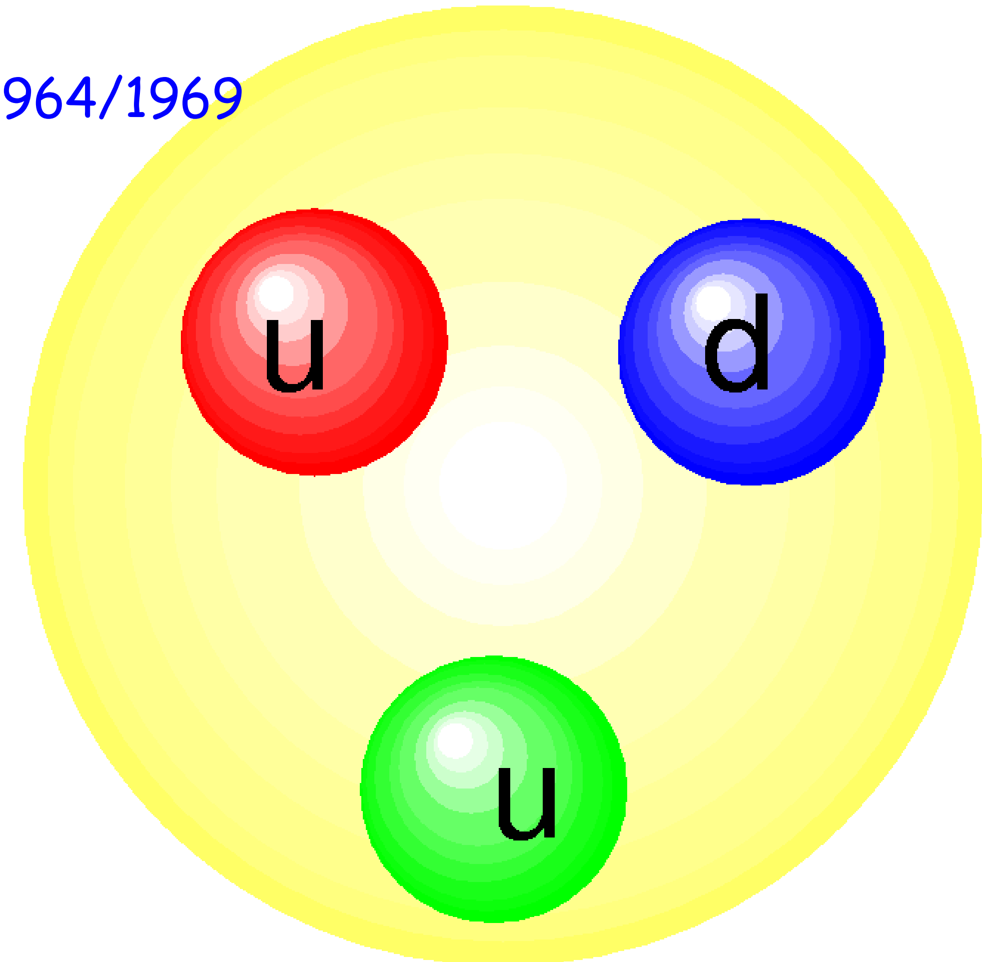
t Hooft 1972/1999
Gross, Wilczek, Politzer 1972/2004

Agree very well with perturbative QCD calculations

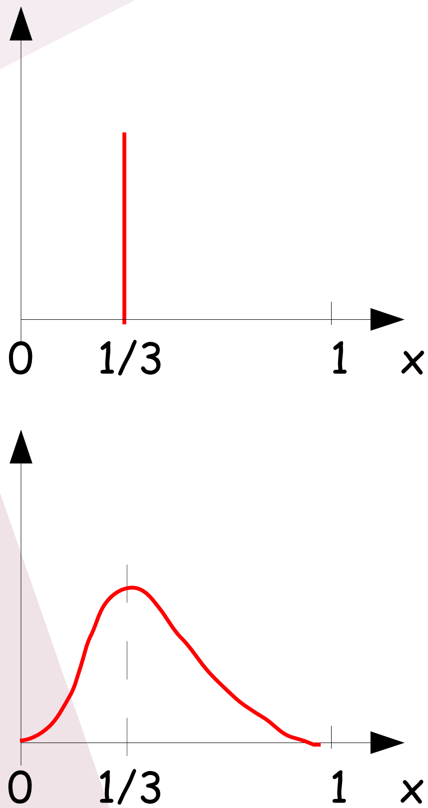
How Does the (inside of) Nucleon Look Like?

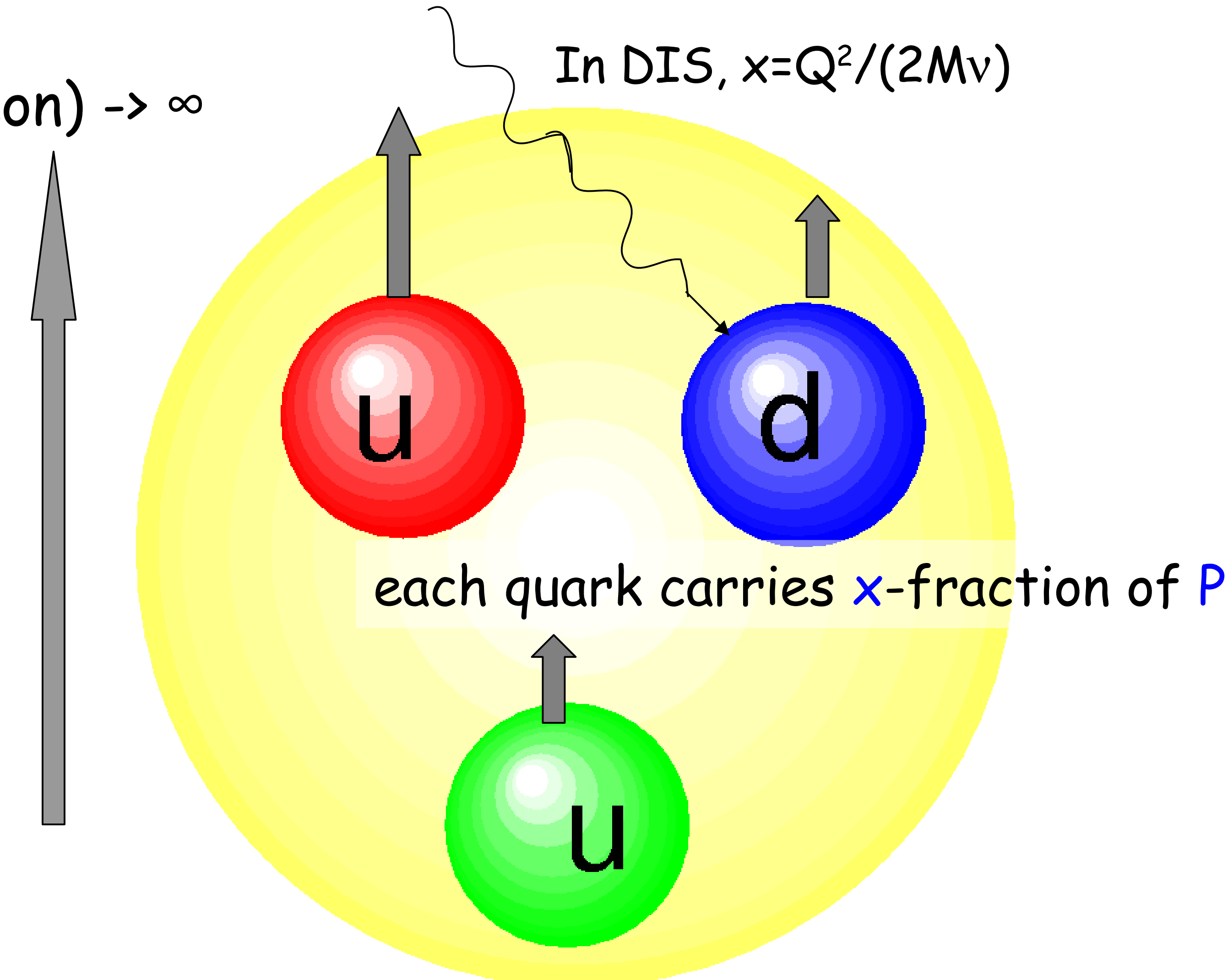
The simple quark model of hadrons

Gell-Mann (Nishijima) 1961/1964/1969



Feynman's Quark Parton Model

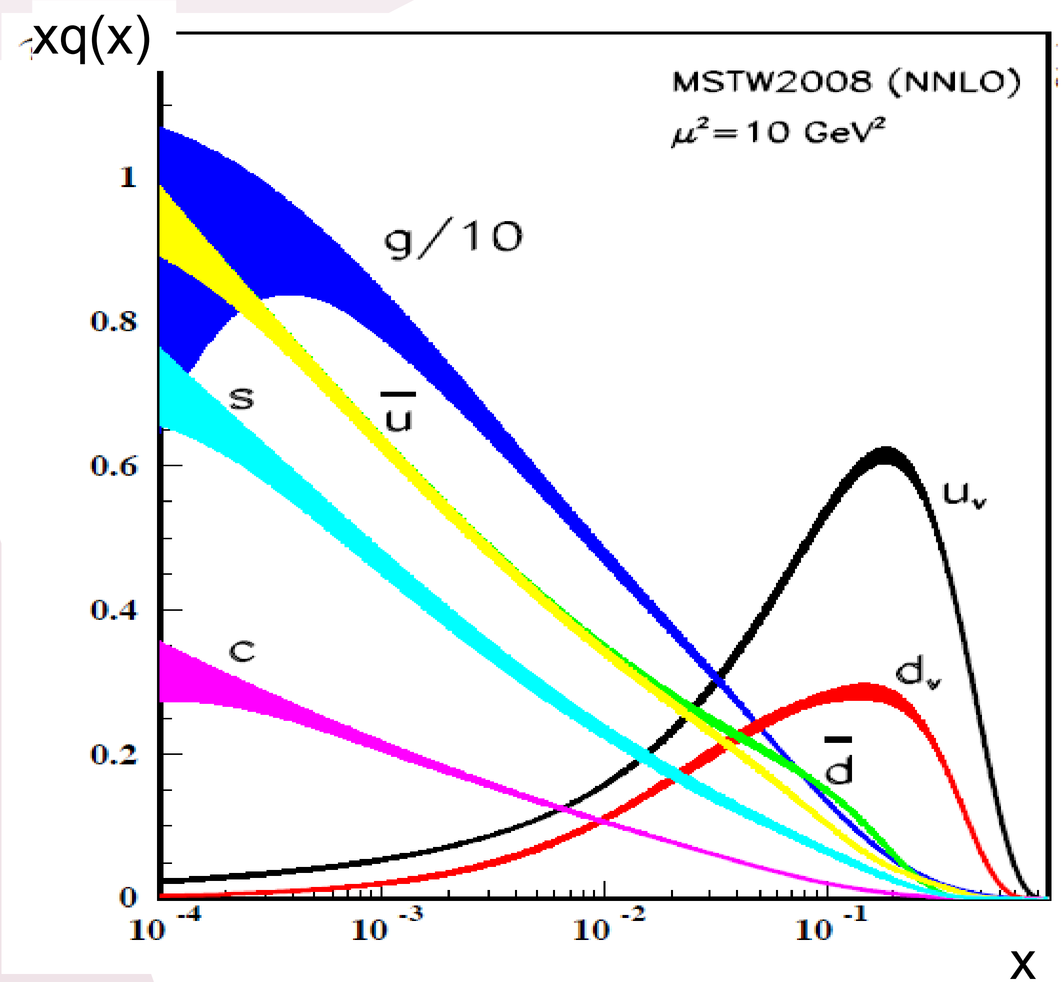


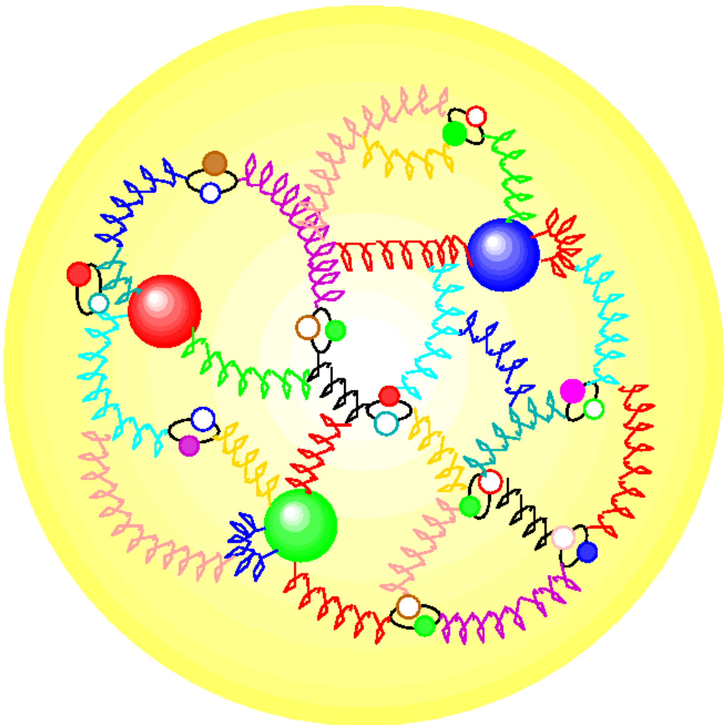


Parton distribution function $q(x)$: Probability to find the u, d, s... quarks carrying x-fraction of the nucleon's momentum

What is the Probability to find a Quark or Gluon at x?

A.D. Martin et al, Eur. Phys. J. C63, 189 (2009)





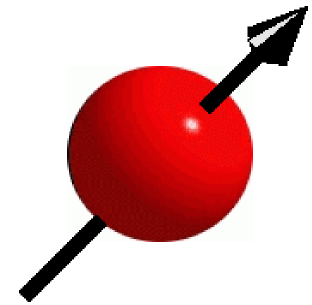
- After four decades of DIS experiments, we know reasonably well how quarks carry the nucleon energy. However, our study of the nucleon has just started... ...

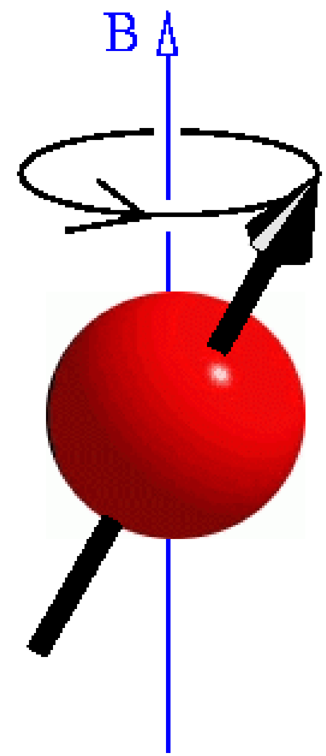
Adding one more Degree of Freedom:

The SPIN

Spin and Polarized Deep Inelastic Scattering

- Spin describes particles' intrinsic angular momentum;
- Spin follows rules of angular momentum;
- Spin allows magnetic moment — a small magnet, interacts with magnetic field (wide applications:)
- Fundamental interactions are often spin-dependent

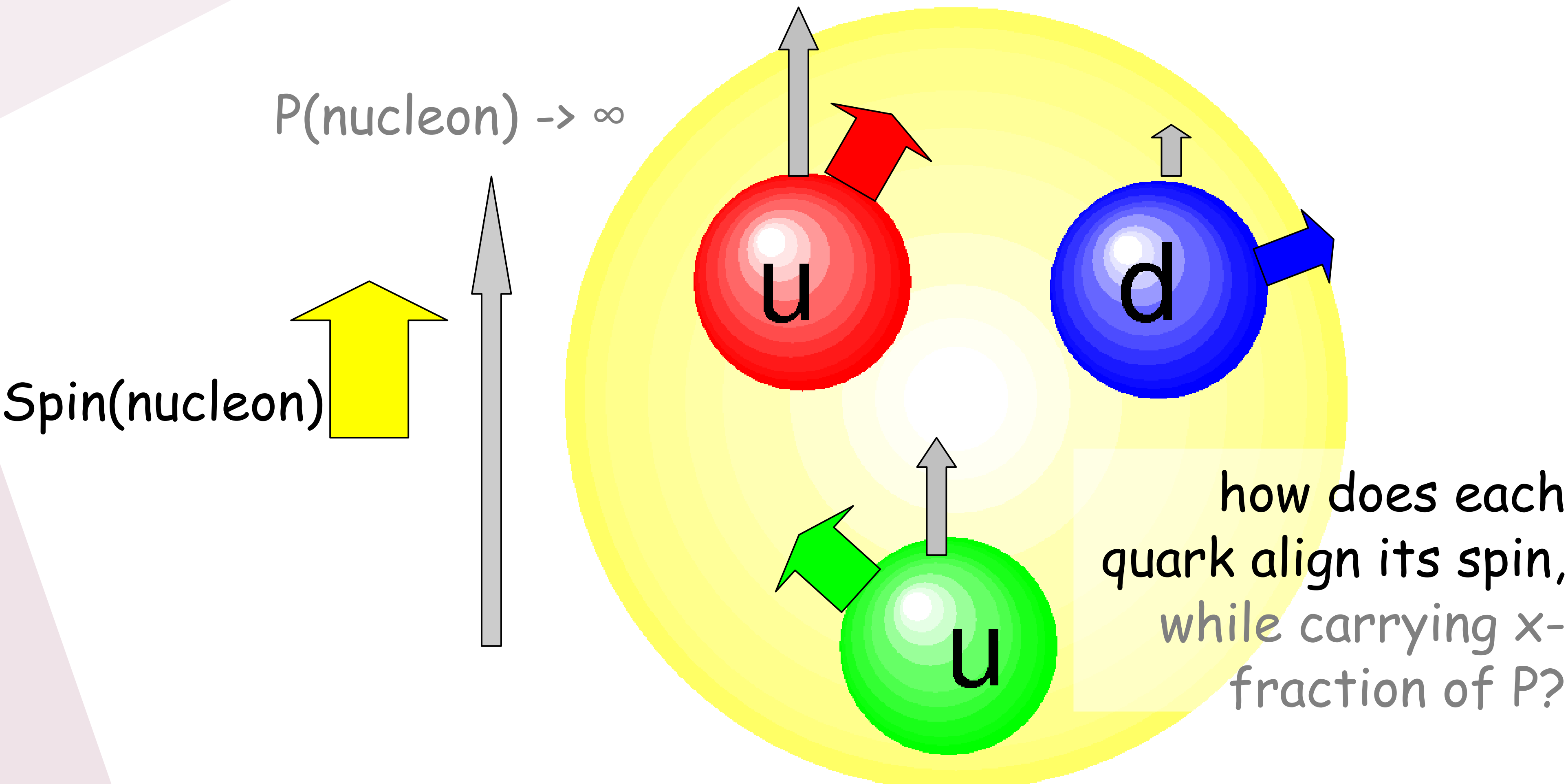




- Scattering cross section is spin-dependent (imaging throwing two small magnets together)

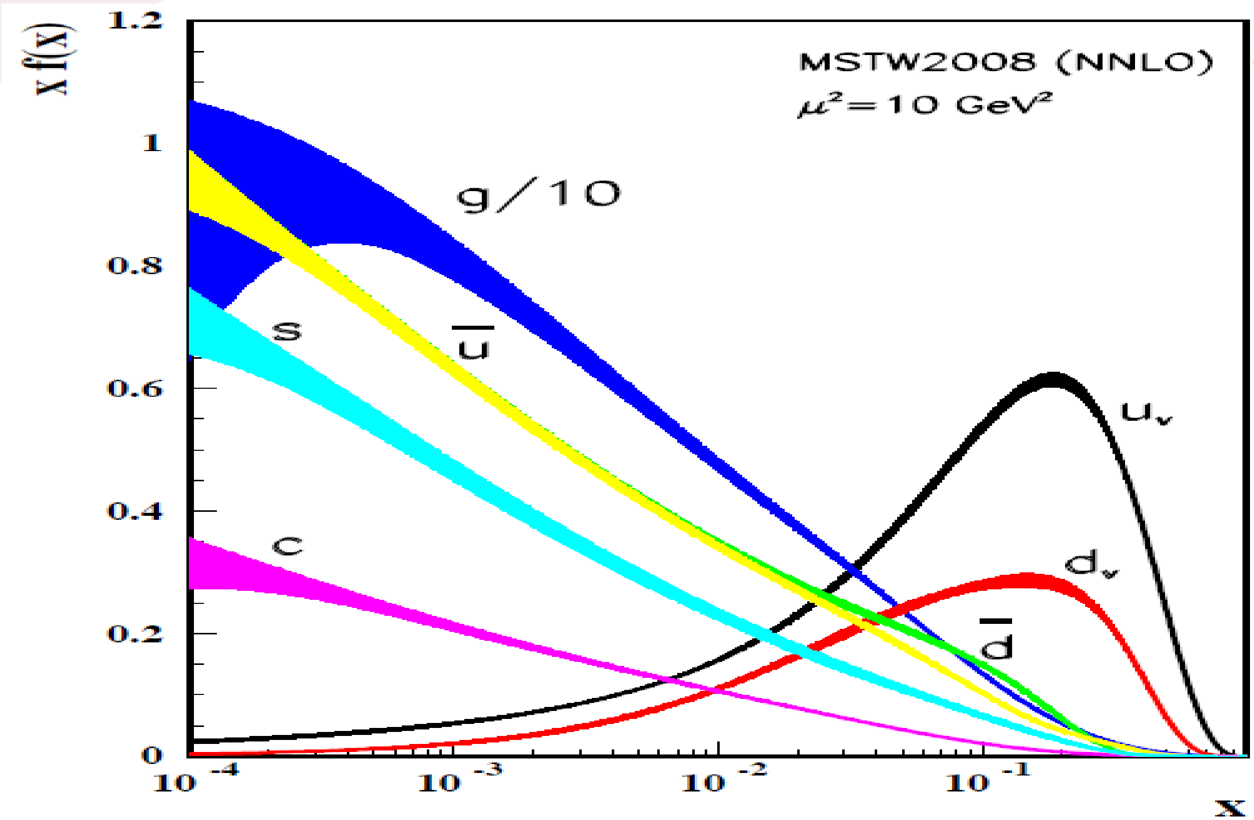
vs.

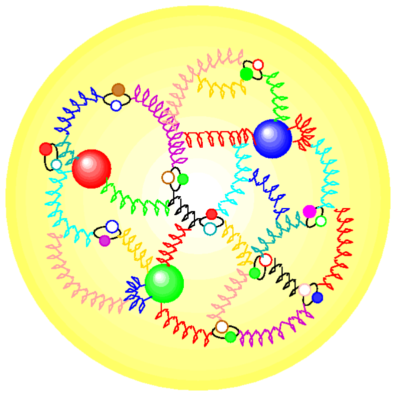
How Are Quarks Polarized Inside the Nucleon?



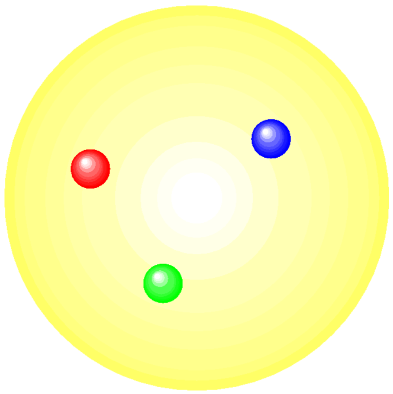
Polarized parton distribution function $\Delta q(x)$: $\Delta u(x)/u(x)$, $\Delta d(x)/d(x)$, $\Delta\bar{u}(x)/\bar{u}(x)$, $\Delta\bar{d}(x)/\bar{d}(x)$ ... ...

Question: Do Data Agree with (QCD) Calculations?





We need to work
with Valence Quarks!
(large x)



Predictions for Valence Quark Polarizations

$$|p^{\uparrow}| = \frac{1}{\sqrt{2}}|u^{\uparrow}(ud)_{00}| + \frac{1}{\sqrt{18}}|u^{\uparrow}(ud)_{10}| - \frac{1}{3}|u^{\downarrow}(ud)_{11}|$$
$$-\frac{1}{3}|d^{\uparrow}(uu)_{10}| - \frac{\sqrt{2}}{3}|d^{\downarrow}(uu)_{11}|$$

based on the symmetry of the 3 quarks' wavefunctions:

Predictions for Valence Quark Polarizations

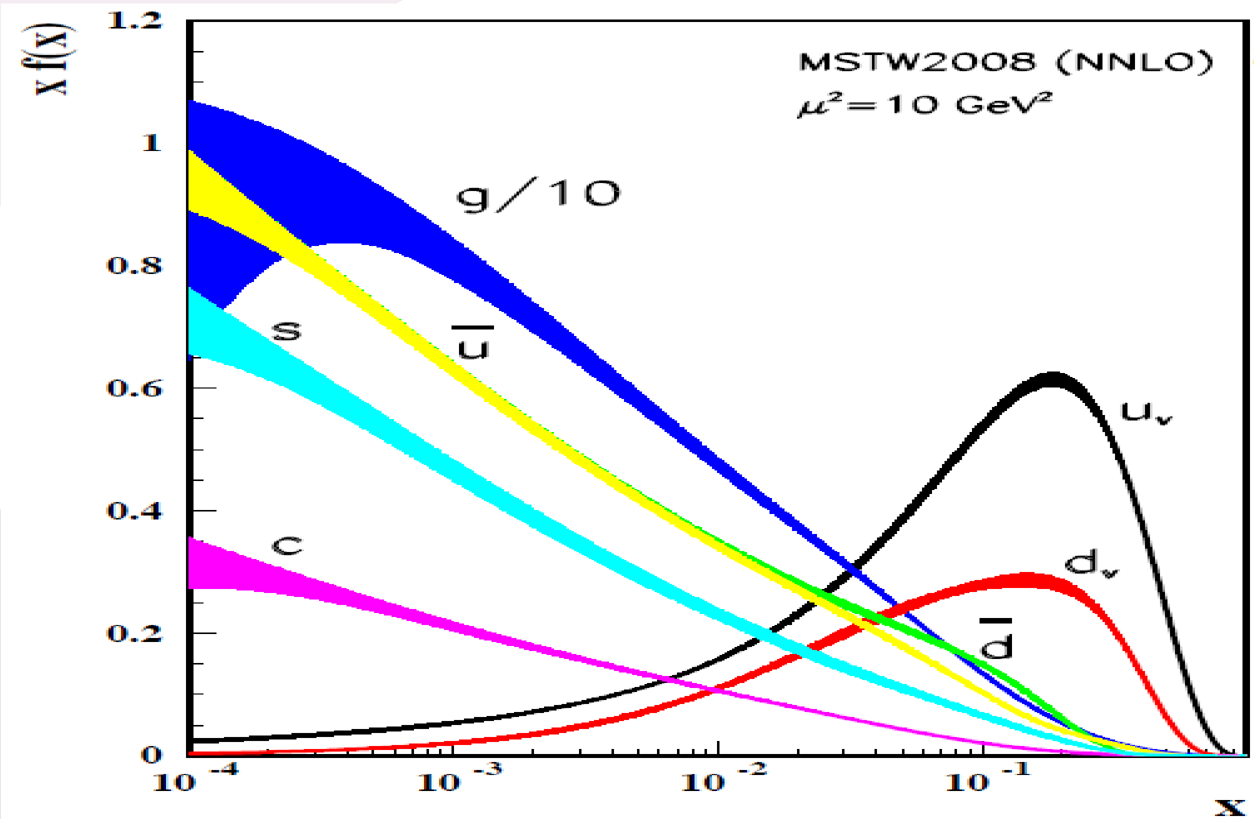
$$|p^{\uparrow}| = \frac{1}{\sqrt{2}}|u^{\uparrow}(ud)_{00}| + \frac{1}{\sqrt{18}}|u^{\uparrow}(ud)_{10}| - \frac{1}{3}|u^{\downarrow}(ud)_{11}|$$
$$-\frac{1}{3}|d^{\uparrow}(uu)_{10}| - \frac{\sqrt{2}}{3}|d^{\downarrow}(uu)_{11}|$$

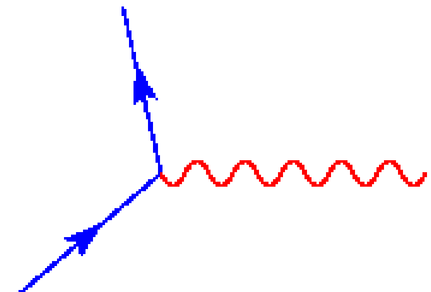
"spin asymmetries"

Model	$\Delta u/u$	$\Delta d/d$	A_1^n	A_1^p
SU(3) flavor (u,d,s) + SU(2) spin	2/3	-1/3	0	5/9
Quark-diquark + hyperfine interaction	1	-1/3	1	1
pQCD + neglecting quark orbital motion	1	1	1	1

$$A_1^p(x) = \frac{(\frac{2}{3})^2 \Delta u(x) + (\frac{-1}{3})^2 \Delta d(x)}{(\frac{2}{3})^2 u(x) + (\frac{-1}{3})^2 d(x)}$$

It's not Easy To Probe the Valence Quarks





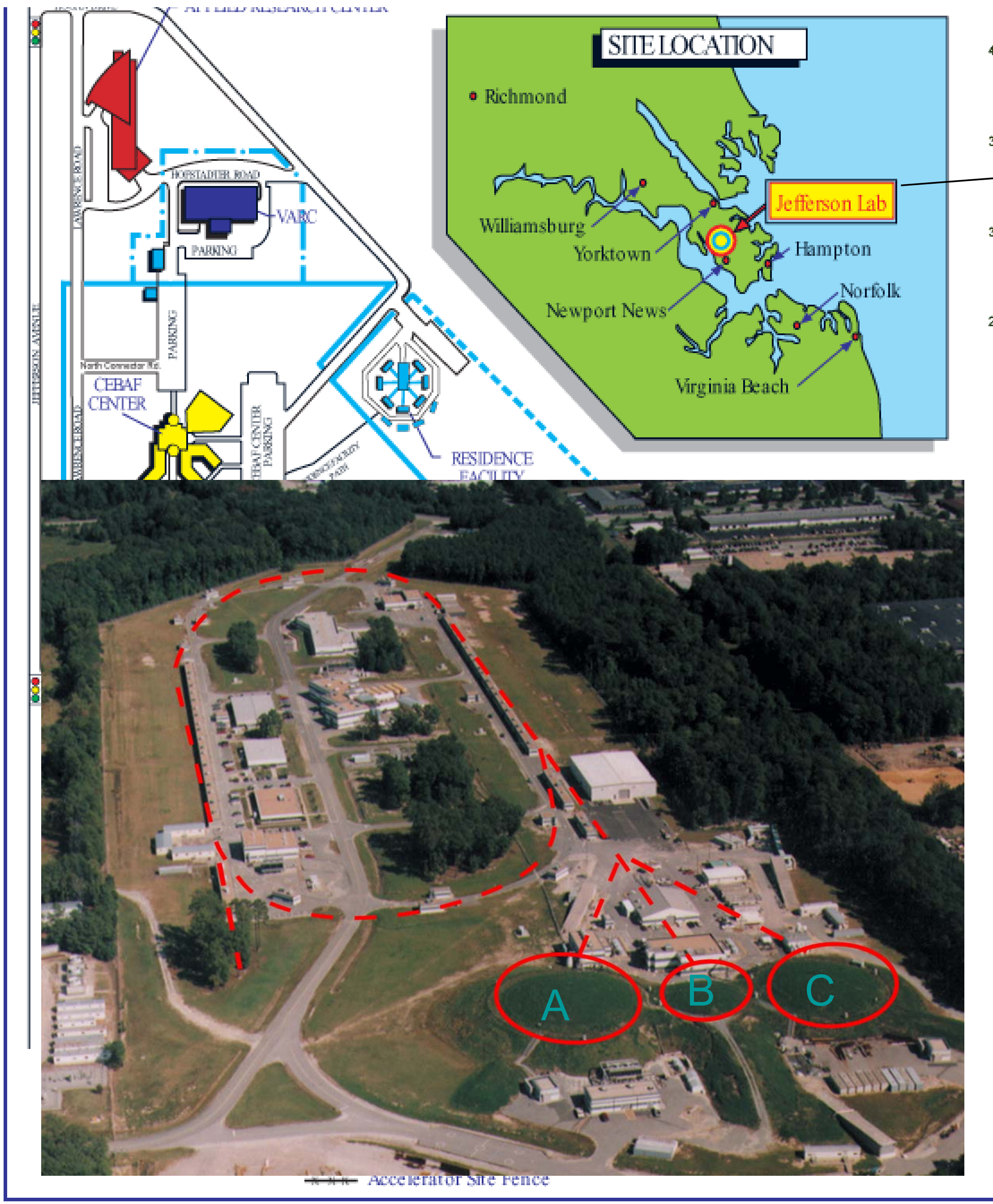
high Q^2 photons "live" shorter

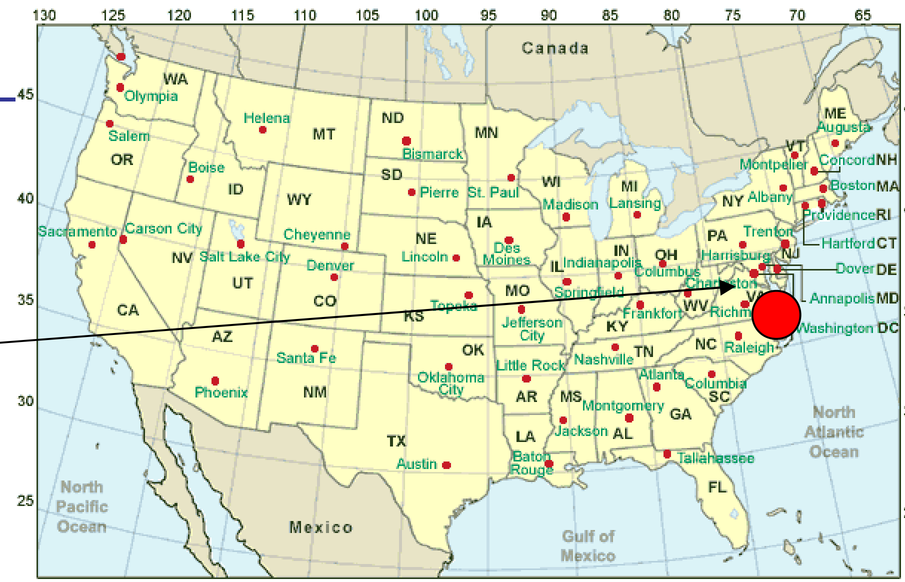
Large x + high Q^2

= doubly small chance to find the quarks

= need high intensity beam and very dense targets (high luminosity)

Jefferson Lab
Thomas Jefferson National Accelerator Facility



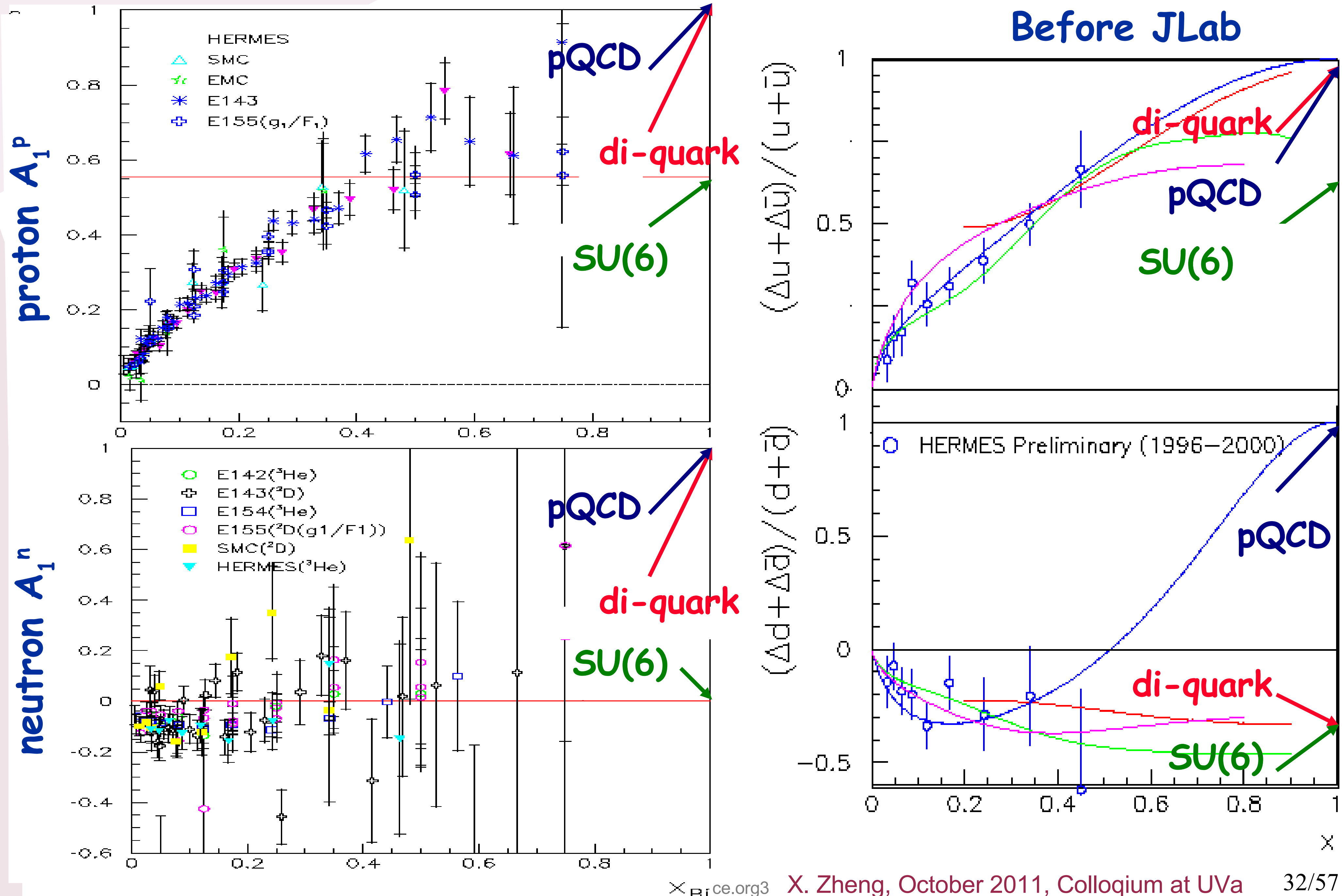


- **Staff: ~650**
- **User community: ~1300**

Unique superconducting radio frequency accelerator provides the highest polarized luminosity of the world

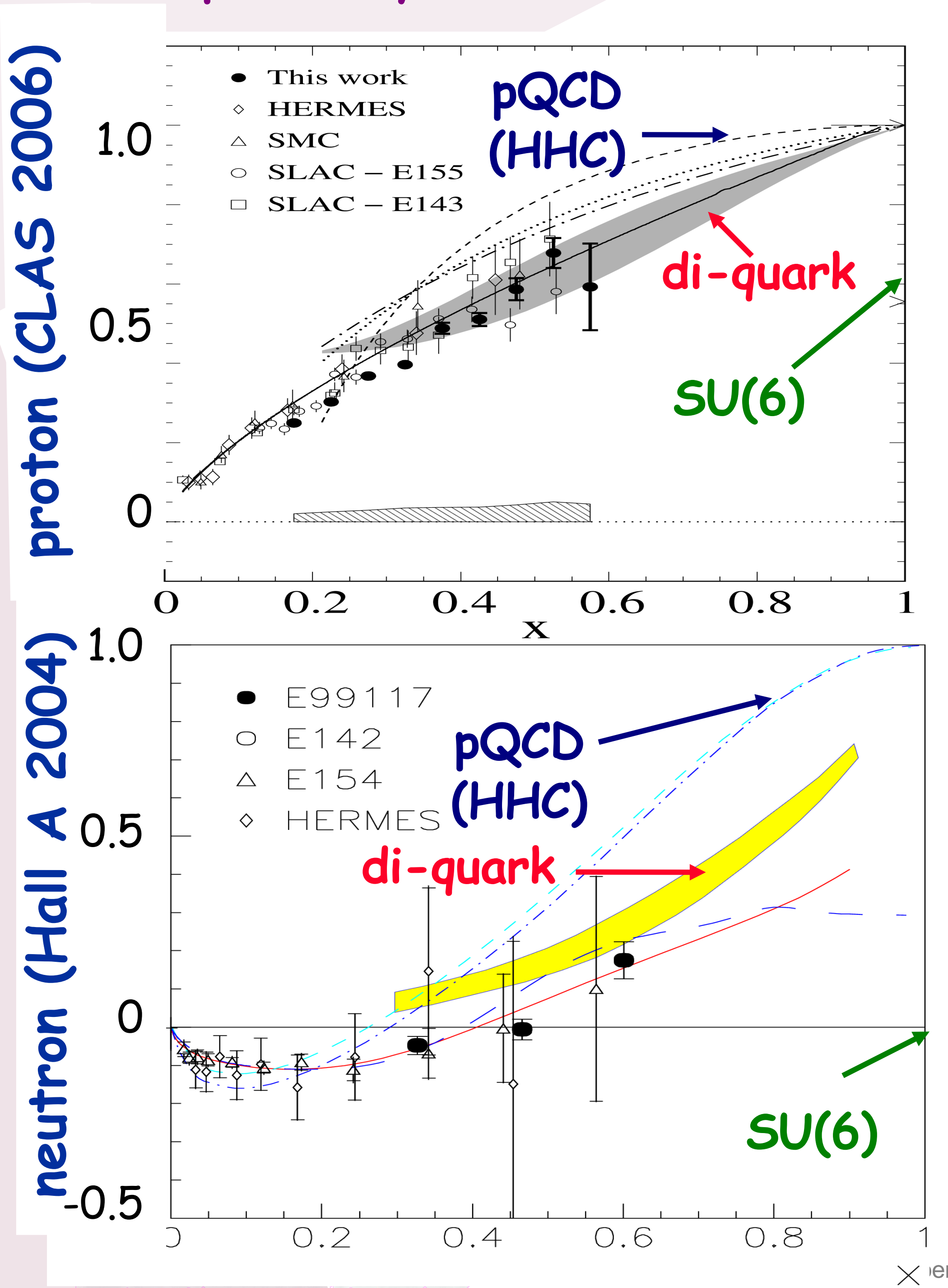
- 334/249 PhDs (~1/3 of US PhDs in Nuclear Physics)
- Energy: 6 GeV(1995-present), 12 GeV (2013)

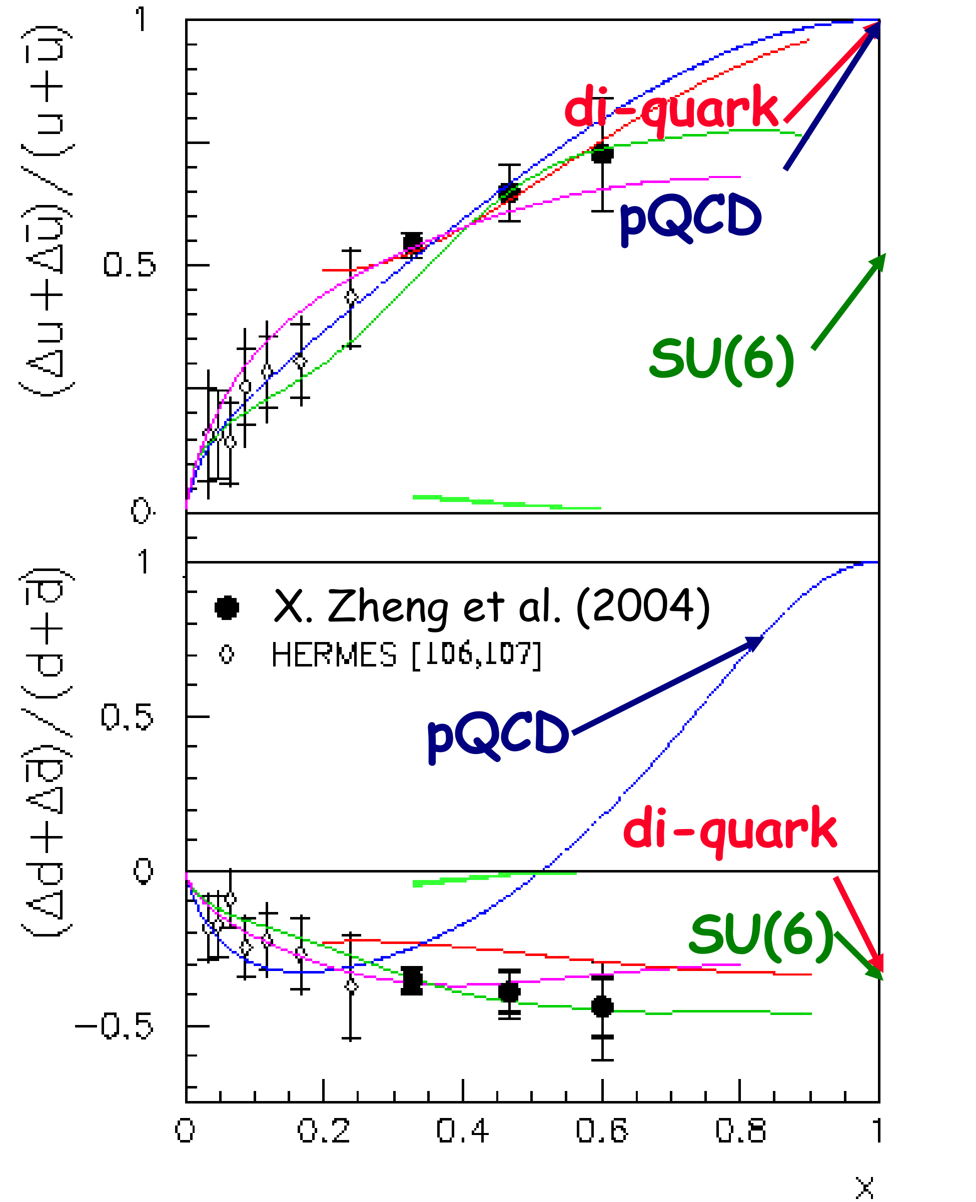
Spin Asymmetries and Valence Quark Polarizations



Spin Asymmetries and Valence Quark Polarizations

with JLab 6 GeV data





What can we learn from the valence quark polarizations?

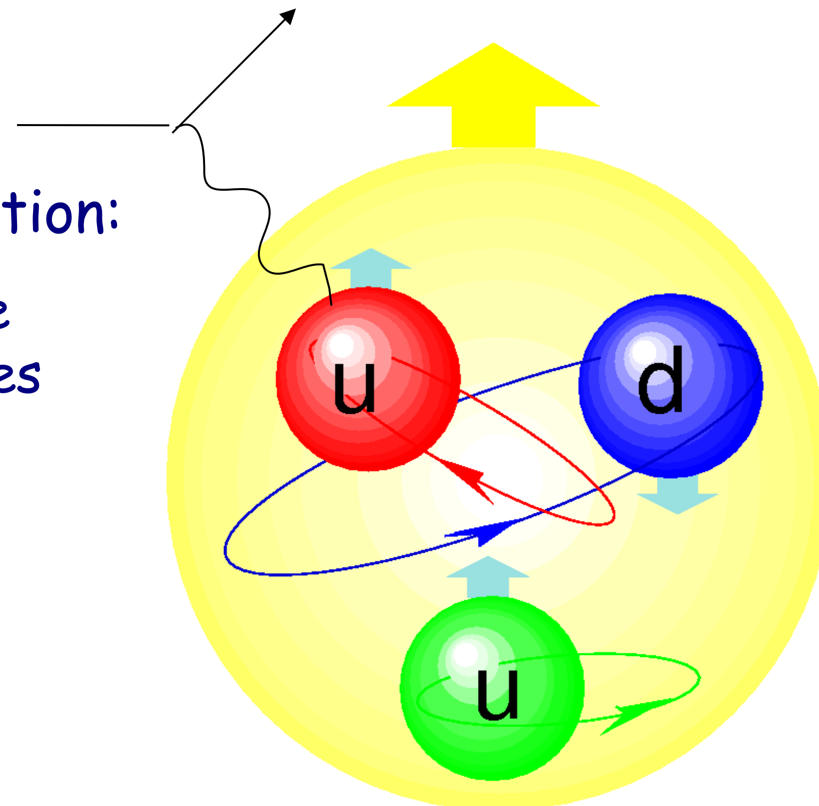
- $\Delta q/q$ describes how the quark is polarized along the nucleon spin

- pQCD+neglecting quark orbital motion:
- the quark carrying x~1 fraction of the nucleon's momentum should also carries the nucleon's spin (pQCD-based);
- the remaining energy is small (1-x), so quark's orbital motion is negligible.

What can we learn from the valence quark polarizations?

- $\Delta q/q$ describes how the quark is polarized along the nucleon spin

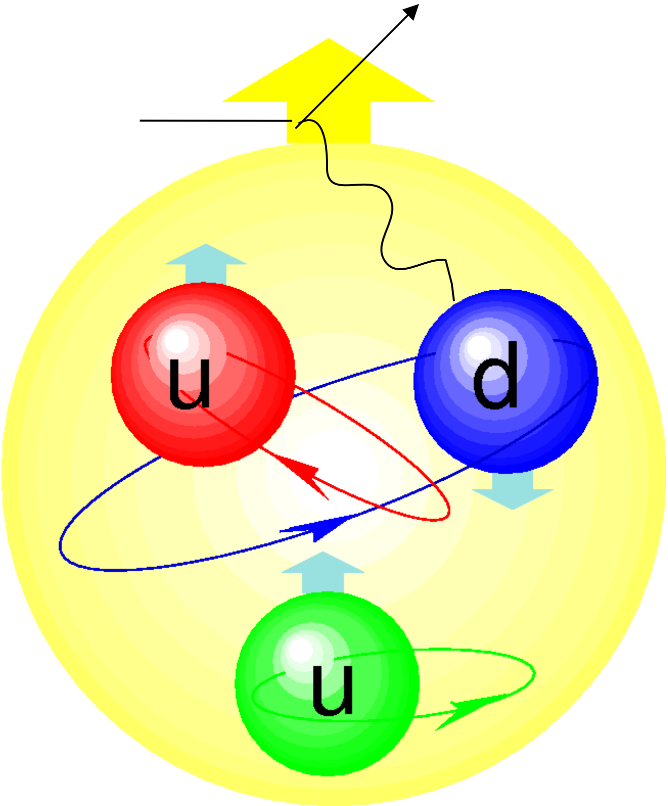
- pQCD+neglecting quark orbital motion:
  - the quark carrying x~1 fraction of the nucleon's momentum should also carries the nucleon's spin (pQCD-based);
  - the remaining energy is small (1-x), so quark's orbital motion is negligible.



What can we learn from the valence quark polarizations?

- $\Delta q/q$ describes how the quark is polarized along the nucleon spin

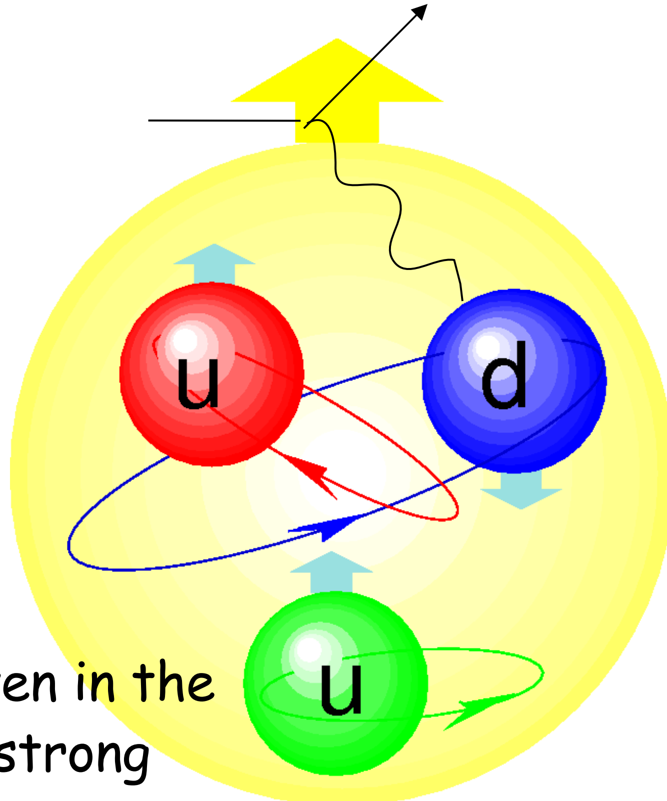
- pQCD+neglecting quark orbital motion:
- the quark carrying x~1 fraction of the nucleon's momentum should also carries the nucleon's spin (pQCD-based);
- the remaining energy is small (1-x), so quark's orbital motion is negligible.



What can we learn from the valence quark polarizations?

- $\Delta q/q$ describes how the quark is polarized along the nucleon spin

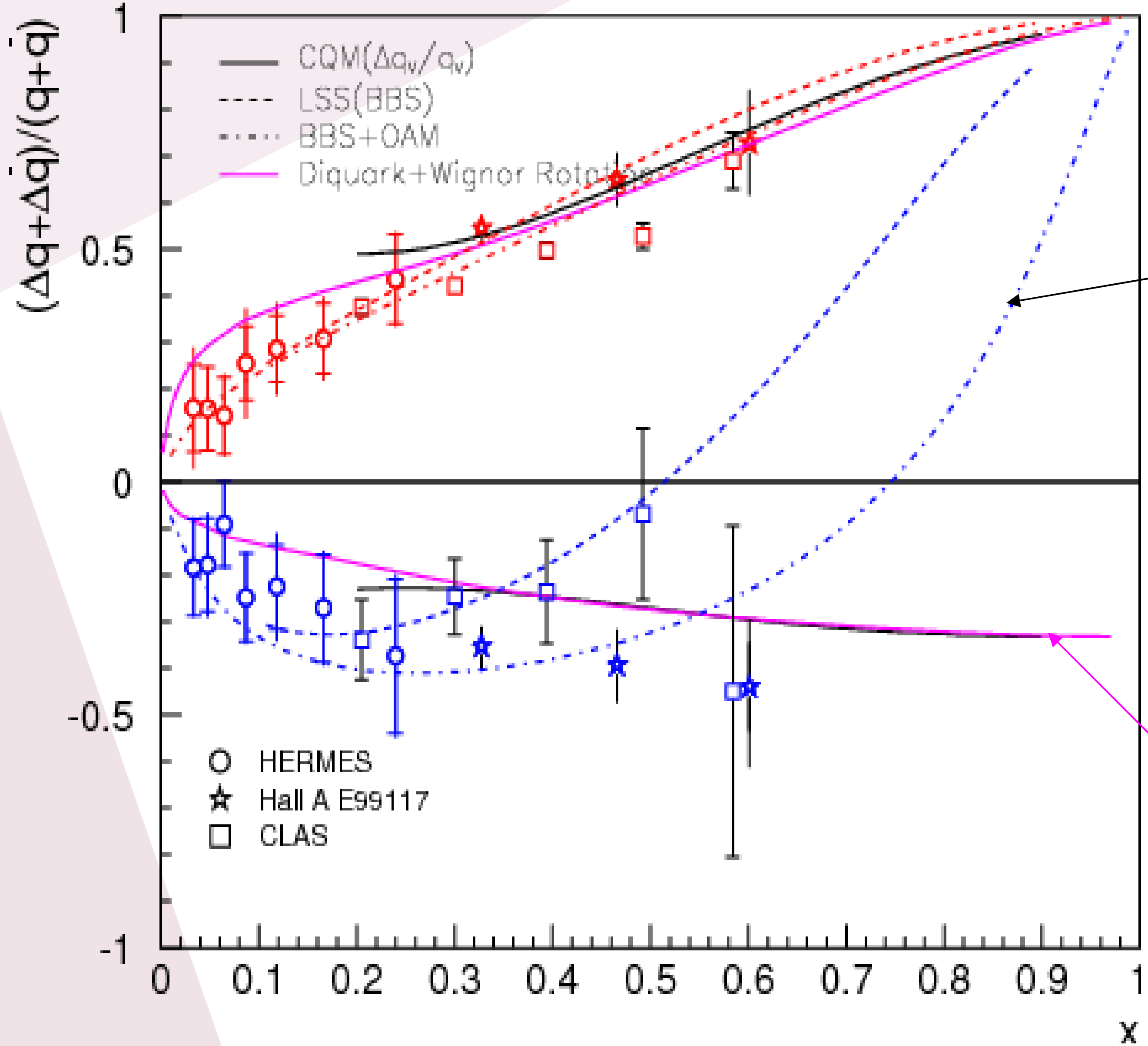
- pQCD+neglecting quark orbital motion:
  - the quark carrying x~1 fraction of the nucleon's momentum should also carries the nucleon's spin (pQCD-based);
  - the remaining energy is small (1-x), so quark's orbital motion is negligible.



- The quark orbital motion is NOT negligible even in the highly energetic, large *x* region – **How?** Does strong interaction force the down quark to align opposite to the proton spin? Is the diquark hyperfine interaction strong enough to flip the down quark?

The JLab Hall A data were quoted in the 2007 long range plan of the US Nuclear Science Advisory Committee as one of the "most important accomplishments since the 2002 LRP";

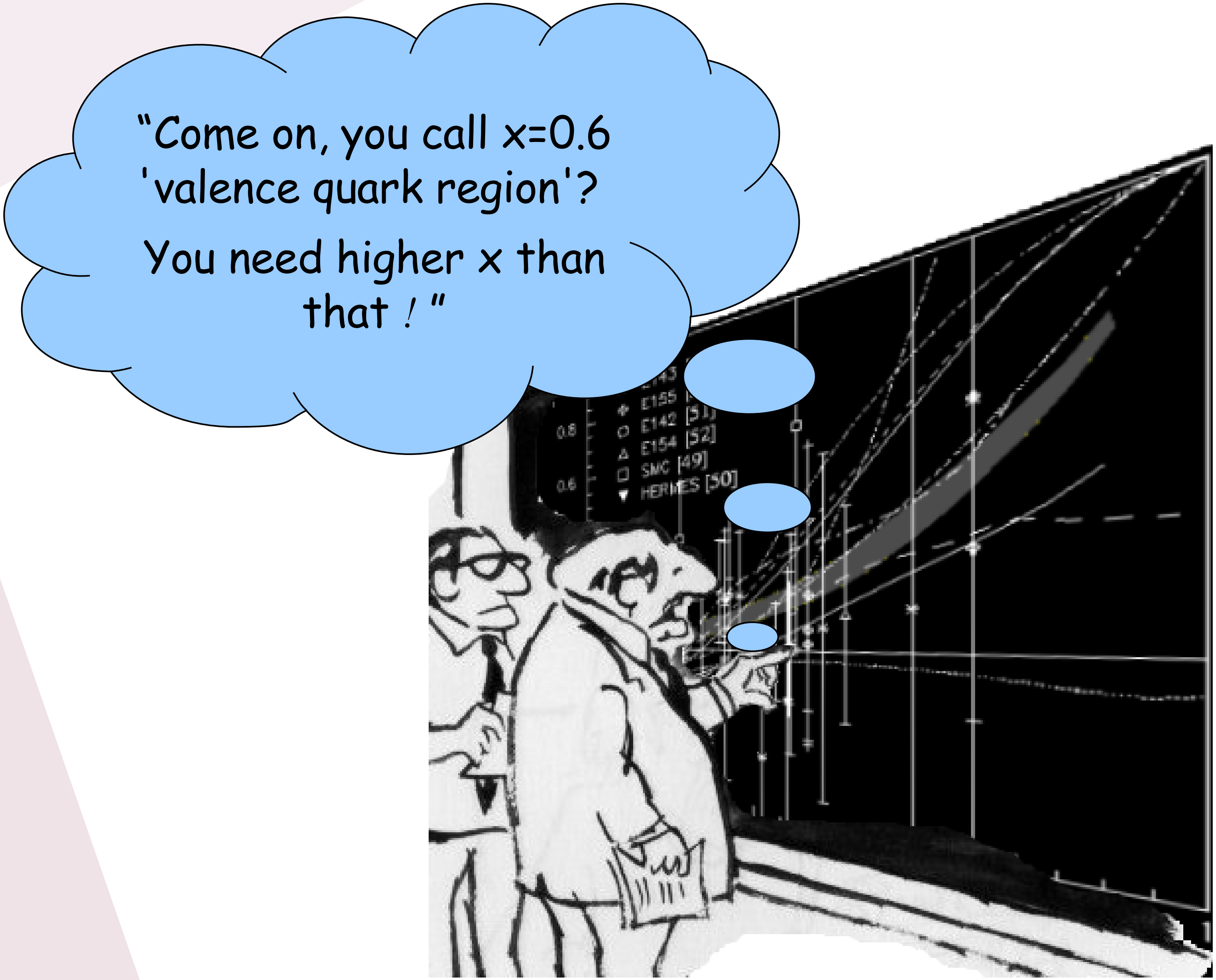
Including the Quark Orbital Angular Momentum?



H. Avakian, S. Brodsky, A. Deur, F. Yuan, Phys. Rev. Lett.99:082001(2007)

light-cone quark/diquark model X. Chen, Y. Mao, B.-Q. Ma, Nucl. Phys. A 759, 188 (2005)

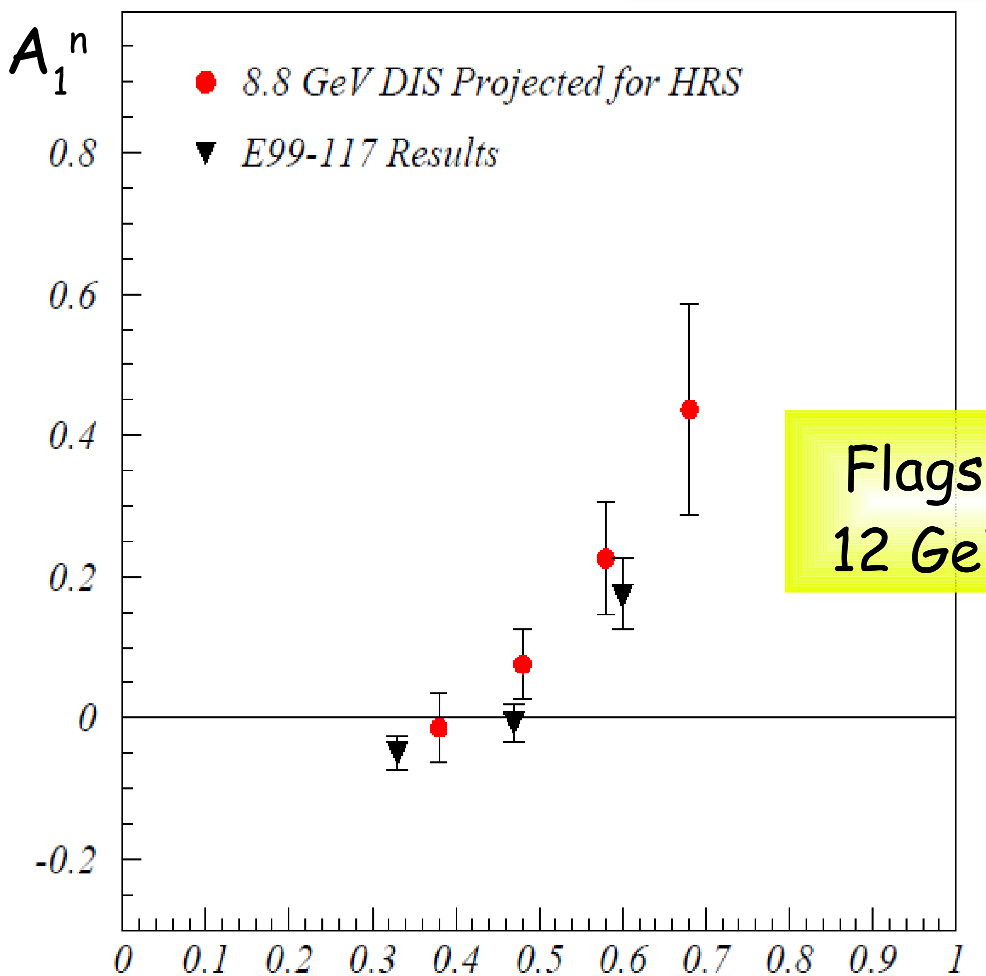
(The Most) Frequently Asked Question

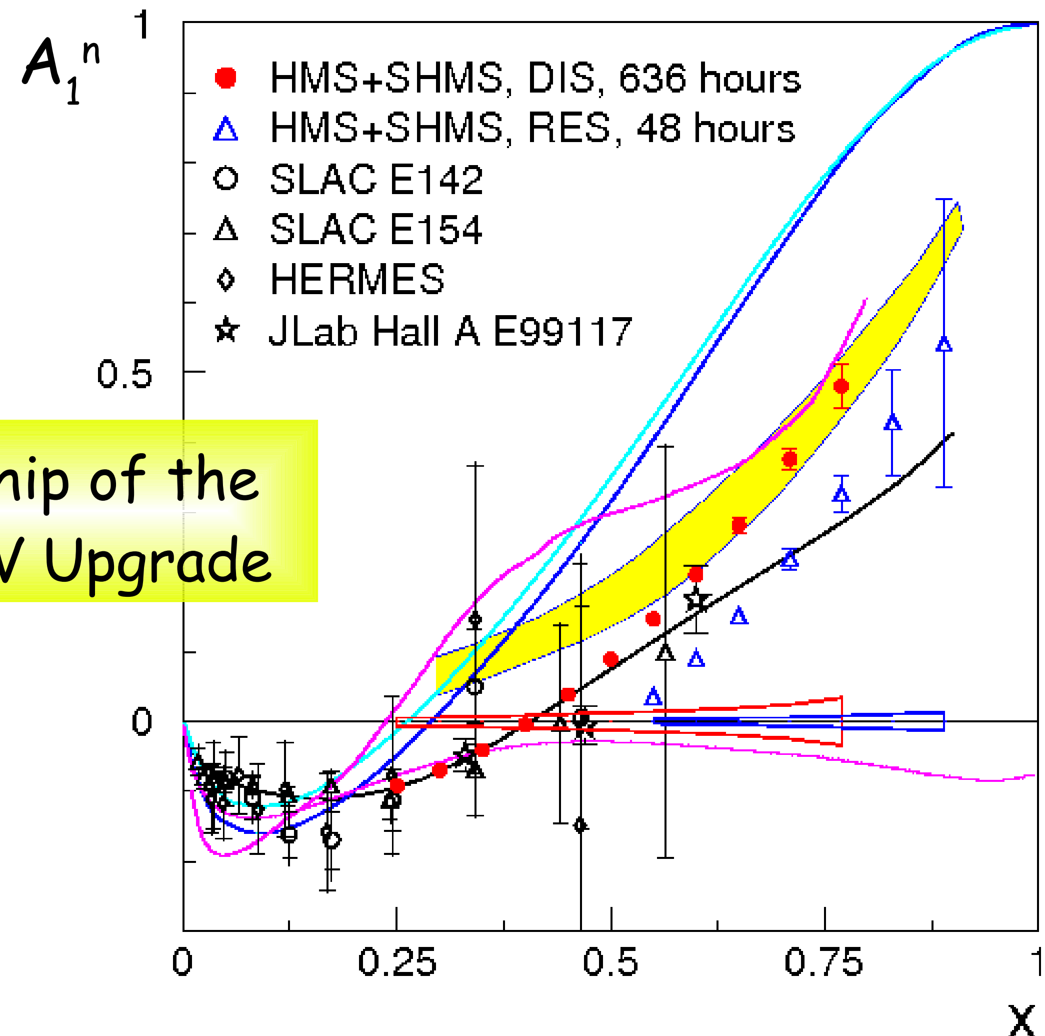


The Planned JLab 12 GeV Neutron Measurement

Hall A spokespeople:
G.D. Cates, N.Liyanage, G. Rosner, B.Wojtsekhowski, X. Zheng;
Student: Jie Liu (UVa)
Approved for 23 days, rated A-

Hall C spokespeople:
J.P.Chen, Z.E.Meziani, G.D. Cates, X.Zheng;
Approved for 35 days, rated A

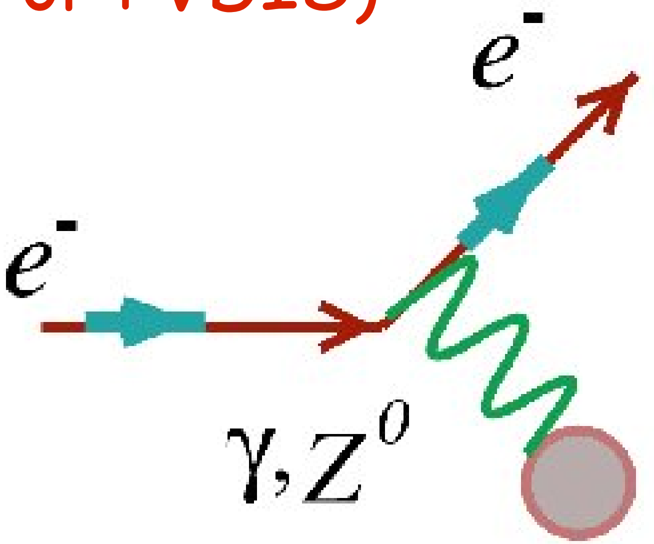




Flagship of the 12 GeV Upgrade

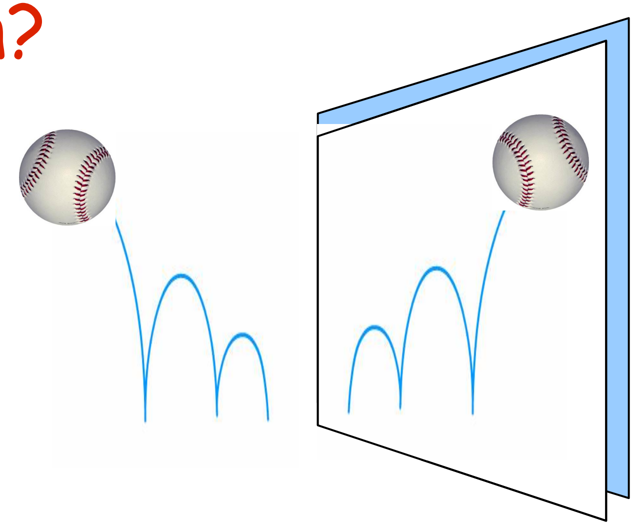
Perhaps Once We Understand the Rules of Spin in Strong Interactions

(Neutral) Weak Interaction in DIS
(Parity Violating DIS, or PVDIS)



What is Parity Violation?

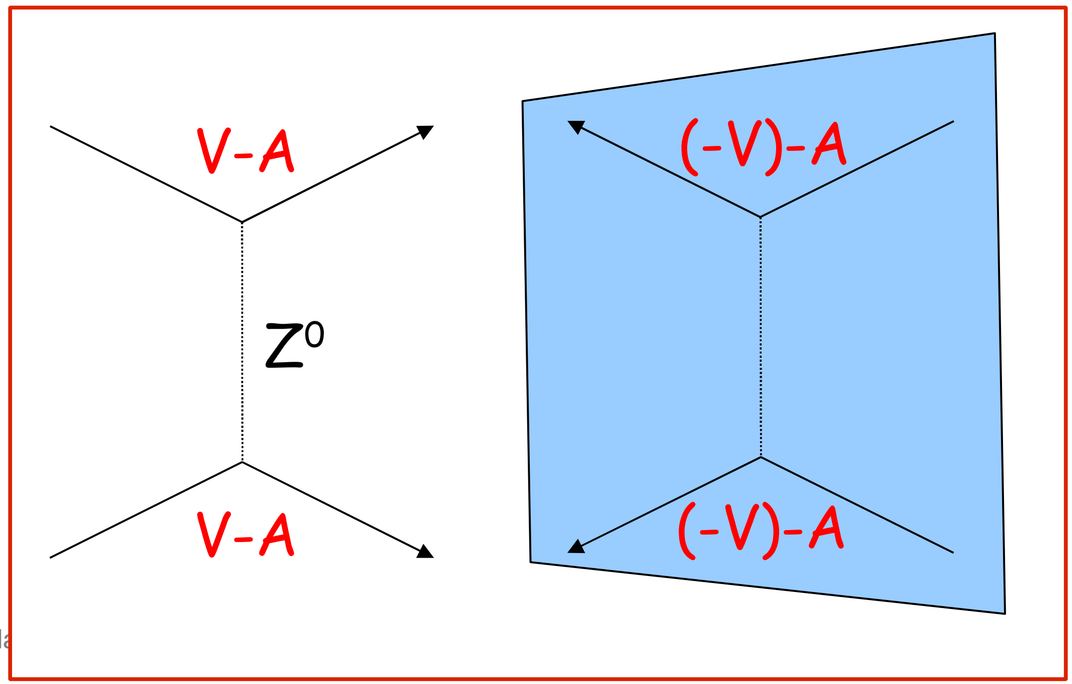
- The parity symmetry: the physical laws behind all phenomena must be the same as those behind their mirror images;
- However this symmetry is broken in weak interactions. Yang, Lee (Wu) 1957/1957



- In the Standard Model,

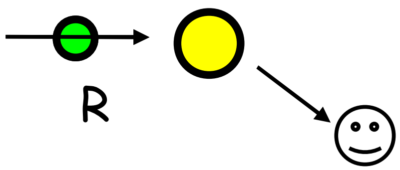
  weak interaction current = V(vector) minus A(axial-vector)

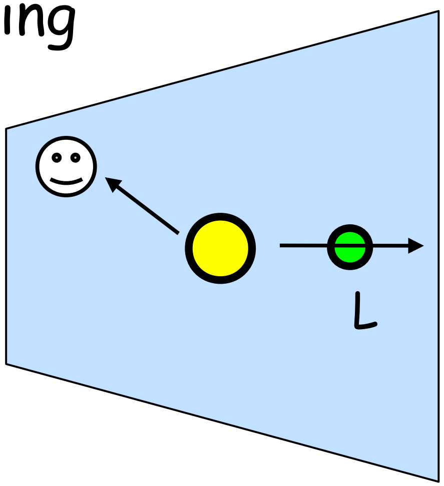
  - Parity violation is from the cross products V x A



Parity Violating Electron Scattering

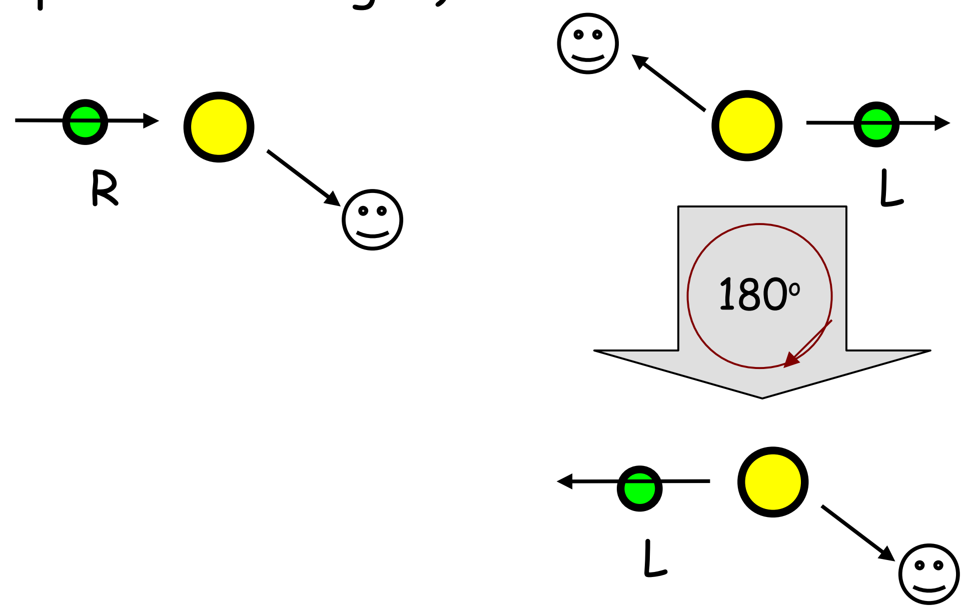
- Weak observable in electron scattering — parity violating asymmetries (A_{PV}) (polarized beam + unpolarized target)





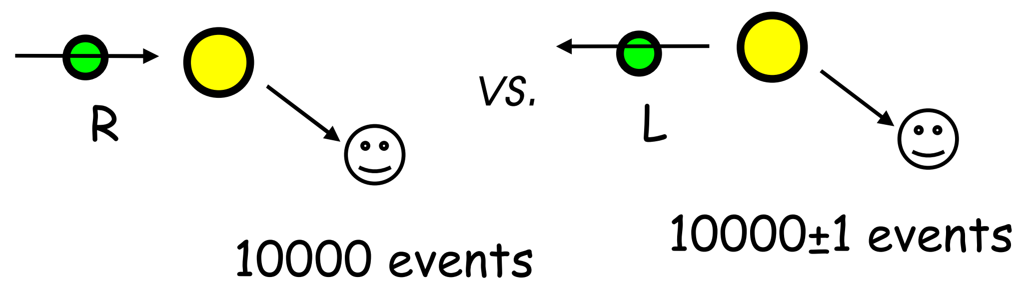
Parity Violating Electron Scattering

- Weak observable in electron scattering — parity violating asymmetries (A_{PV}) (polarized beam + unpolarized target)

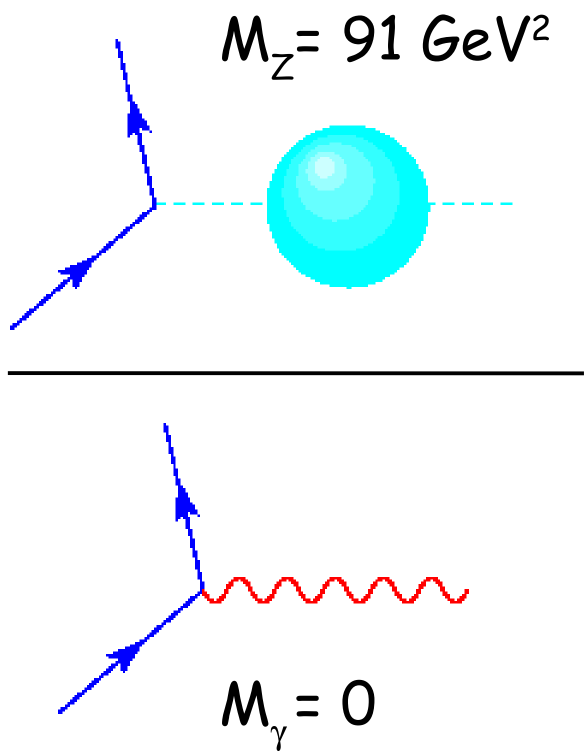


Parity Violating Electron Scattering

- Weak observable in electron scattering — parity violating asymmetries (A_{PV}) (polarized beam + unpolarized target)



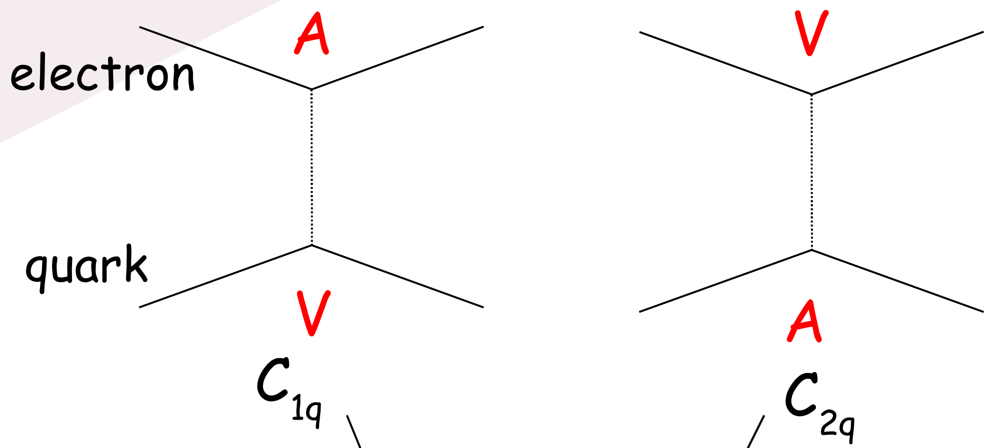
$A_{LR} =$



$$\approx \frac{Q^2}{M_Z^2} \approx 120\ ppm \quad at \quad Q^2 = 1\,(GeV/c)^2$$

Parity Violation in Deep Inelastic Scattering

PV ~



$$A_{PV} \propto Q^2 \left[a(x) + Y(y)\, b(x) \right]$$

a(x), b(x) contain quark distributions

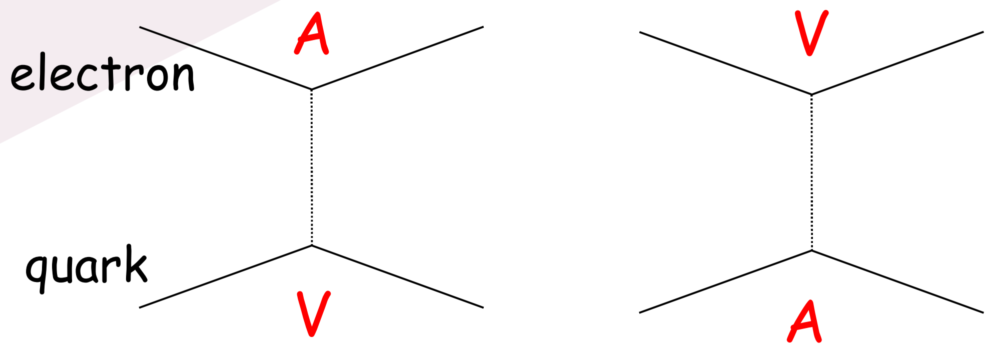
Y(y) contains kinematics

PVDIS can be used to access $C_{1,2q}$s

SLAC E122 (1978):

- The first parity violation electron scattering experiment, also the only PVDIS until 2009
- Established Weinberg & Salam's specific mixing of SU(2) and U(1) as the theory of electroweak unification.

Parity Violation in Deep Inelastic Scattering

PV ~ 

$$A_{PV} \propto Q^2 \left[a(x) + Y(y) b(x) \right]$$

a(x), b(x) contain quark distributions
Y(y) contains kinematics

PVDIS can also access the nucleon structure beyond the simple parton model

Require careful planning!

6 GeV (moderate precision, two kinematics) – accessing the C_{2q}
12 GeV (high precision, wide kinematics) – accessing both.

The 6 GeV JLab PVDIS Measurement (E08-011)

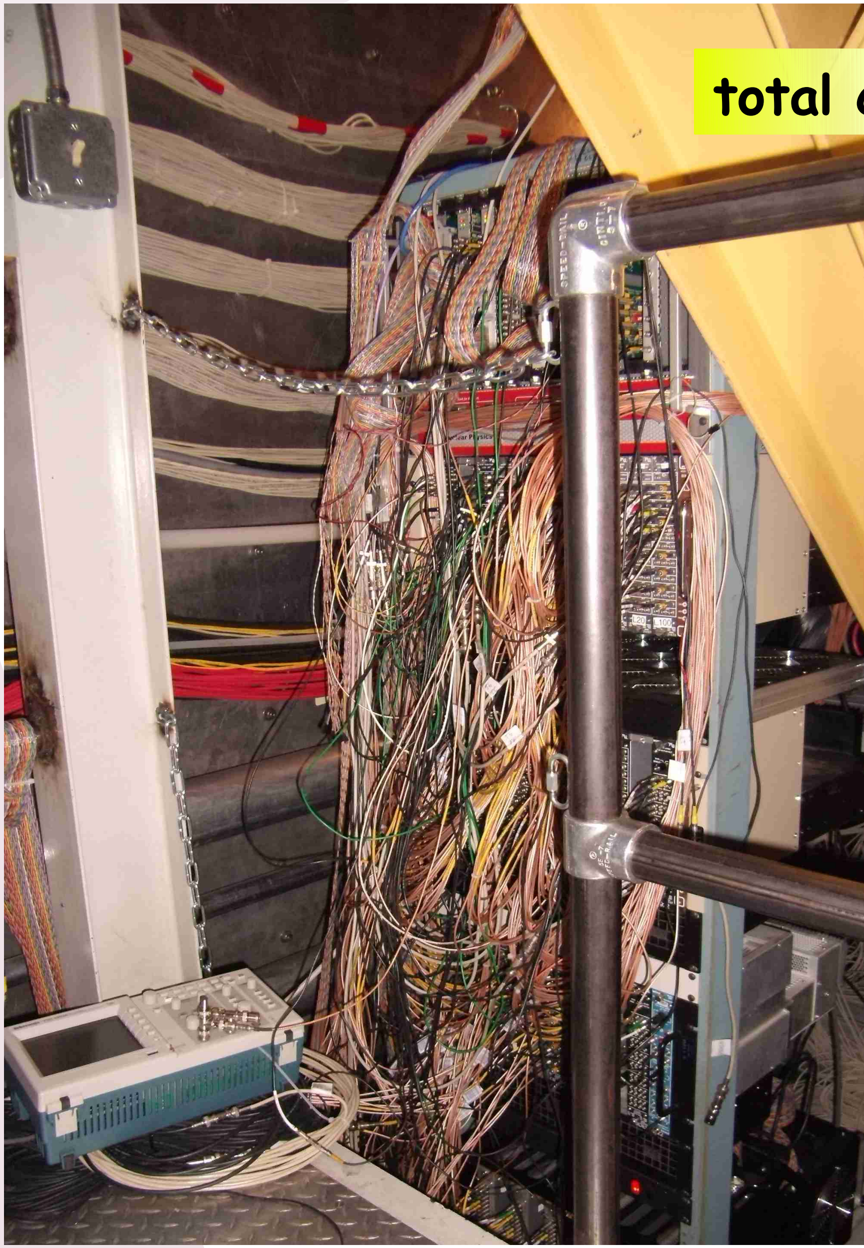
Spokespeople: P.E. Reimer, R. Michaels, X. Zheng
Grad. Students: Kai Pan (MIT), Diancheng Wang (UVa), Xiaoyan Deng (UVa)
Postdoc: Ramesh Subedi

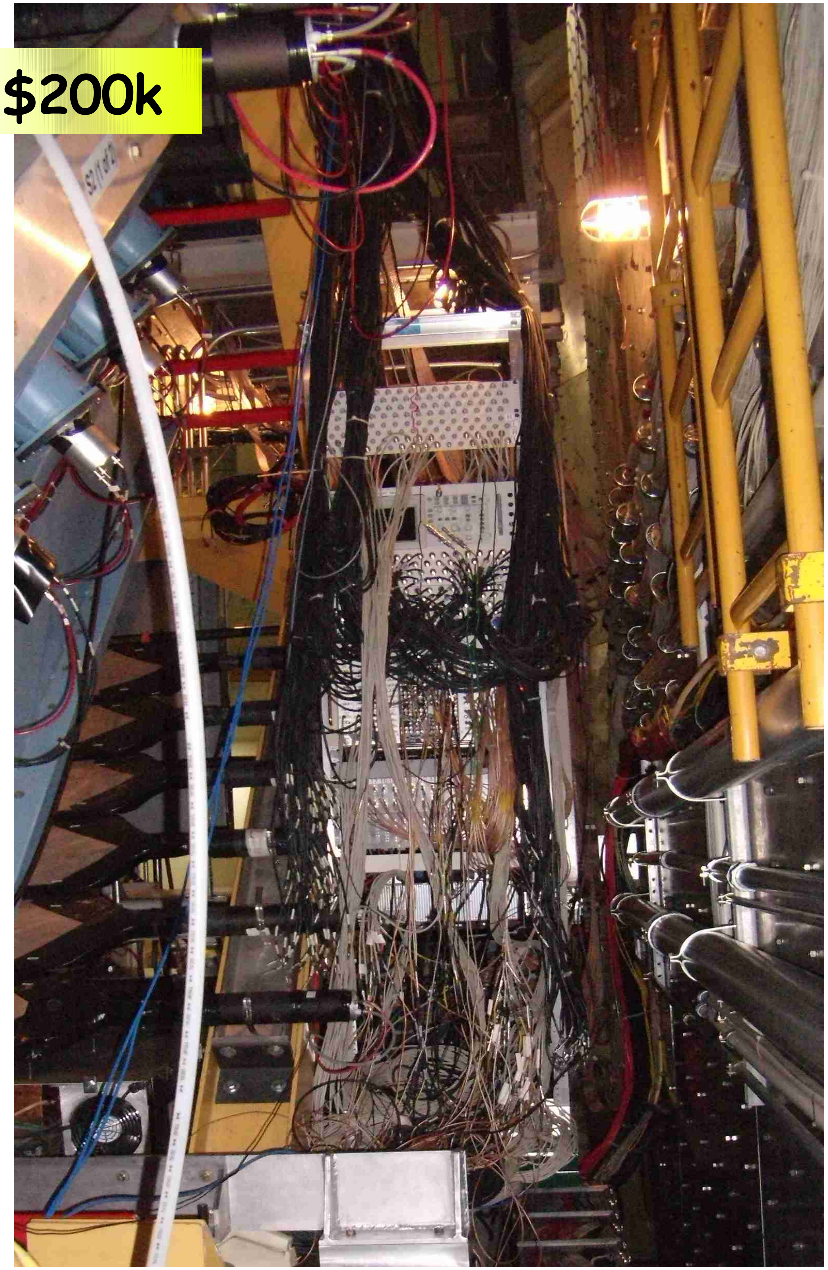
(Hall-A Collaboration Experiment, A- rating)

- Ran successfully from Oct-Dec. 2009 in JLab Hall A;
- 105μA, 6 GeV, 90% polarized beam, helicity flip every 33msec;
- 20-cm liquid deuterium target;
- ~500kHz scattered electron events with high pion background;
- Measure A_{PV} at Q^2=1.10 and 1.90 GeV^2 to 3% and 4% (stat.), systematic uncertainties are smaller.
- Analysis on-going. From the 1.90 GeV^2 point, expect to achieve factor of 5 improvement on $2C_{2u}-C_{2d}$.

It's not easy to count electrons! — Our customized fast counting DAQ with online particle identification

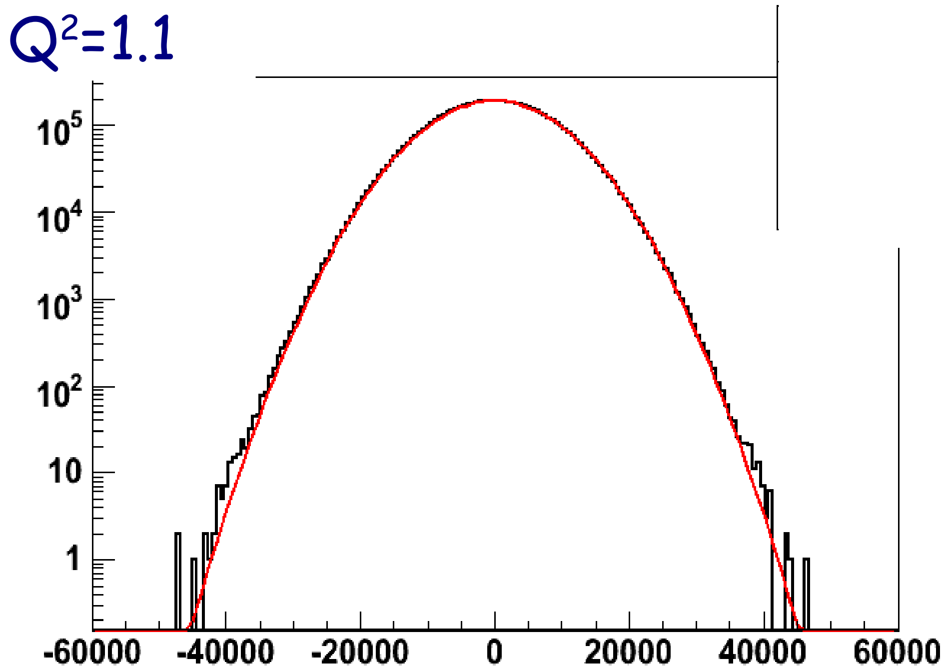
total cost: $200k

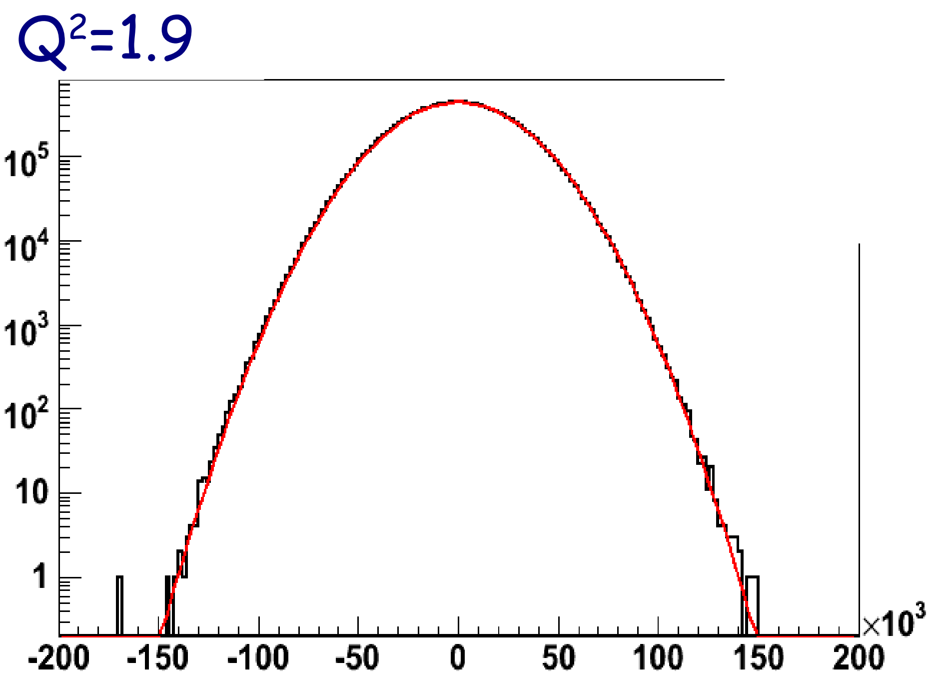




Statistical Quality of Data

purely statistical = pure Gaussian



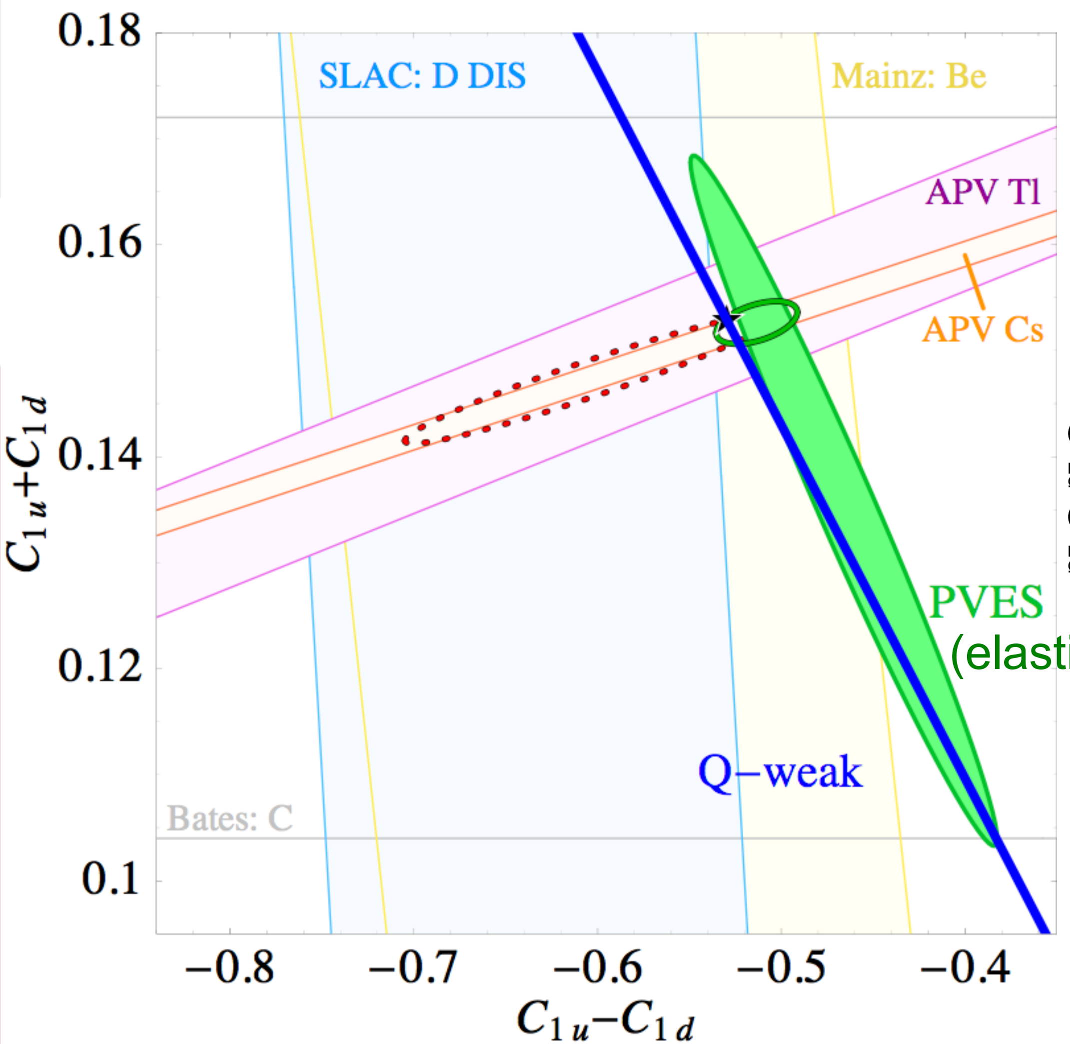


asymmetry of electron counts within 66msec-long beam helicity L/R pairs (in ppm)

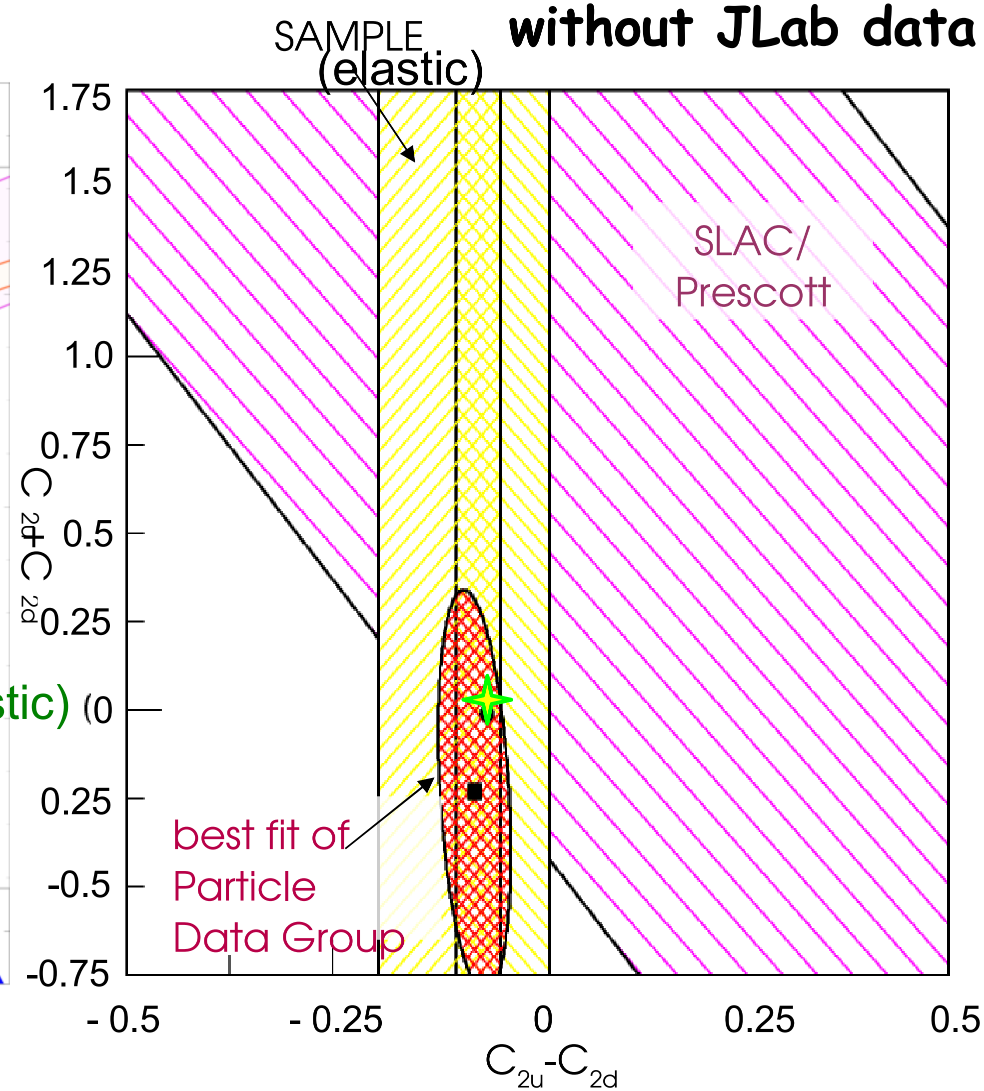
Quark Weak Neutral Couplings $C_{1,2q}$

all are 1 σ limit

with recent PVES data and Qweak



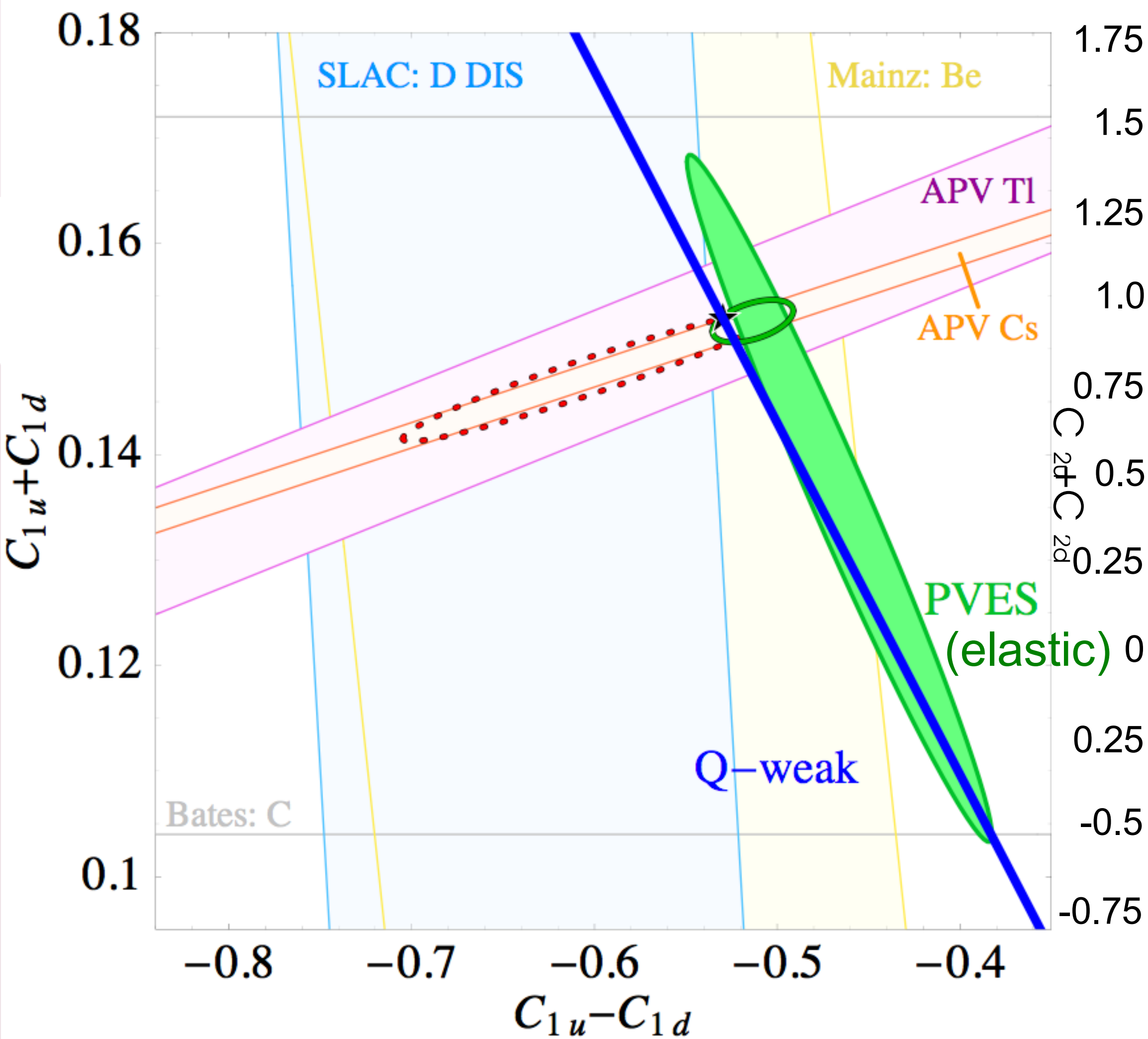
without JLab data



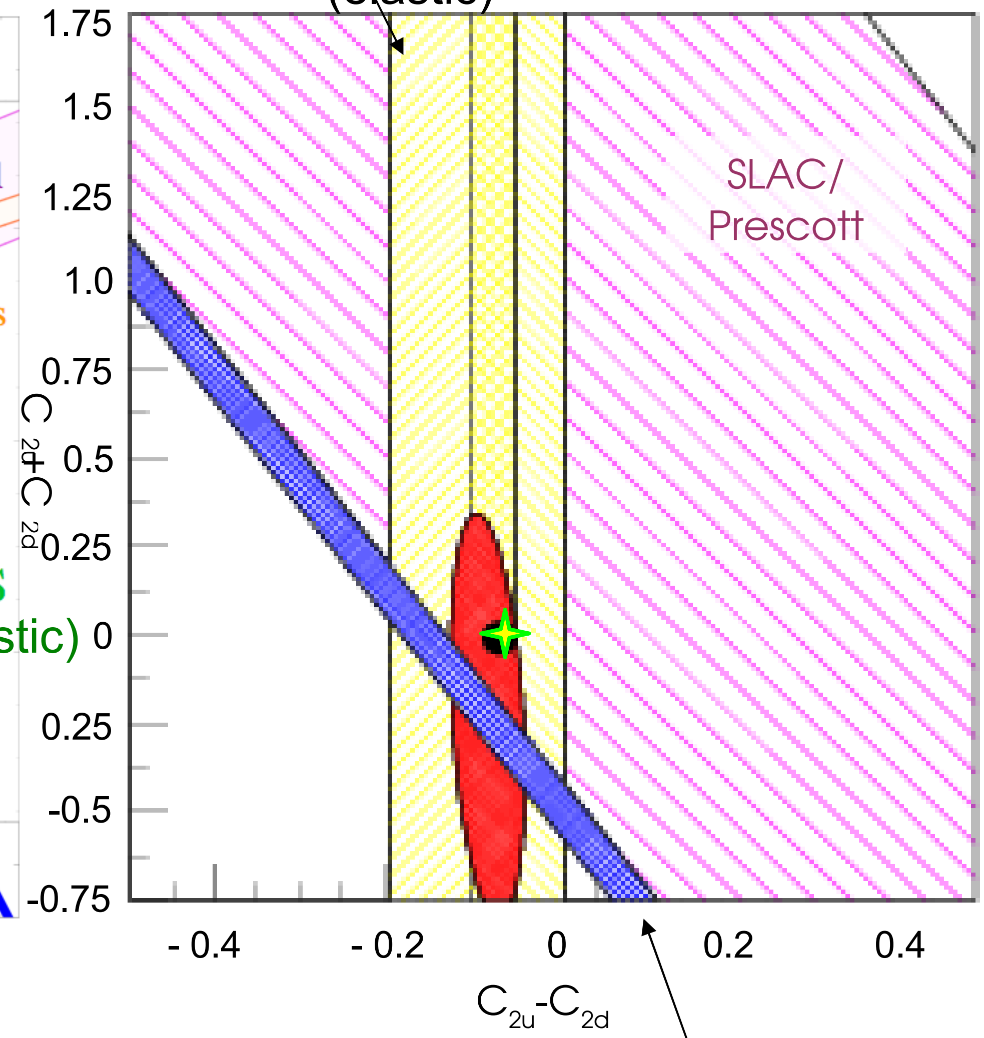
Quark Weak Neutral Couplings $C_{1,2q}$

all are 1 σ limit

with recent PVES data and Qweak



with JLab 6 GeV

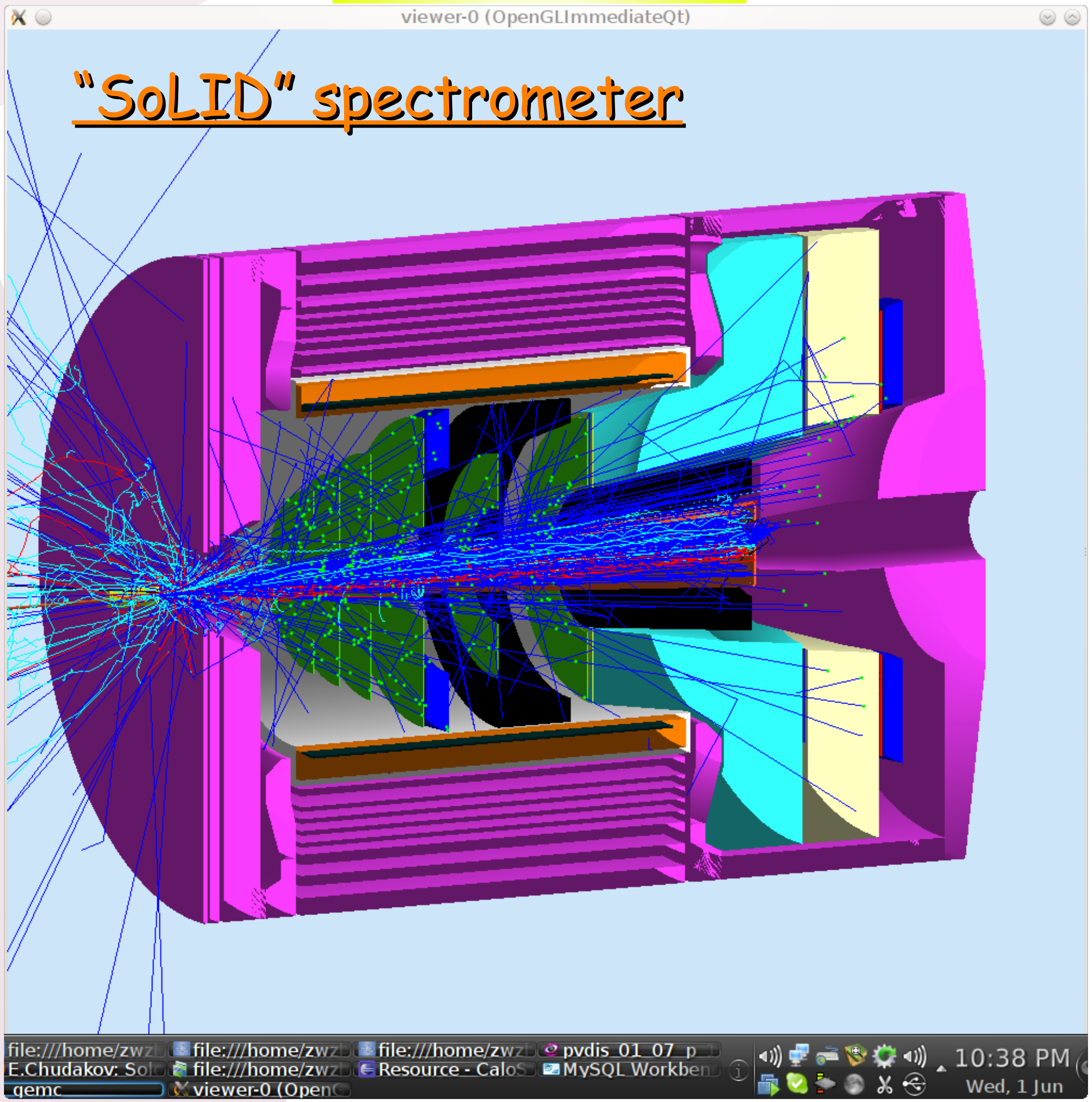


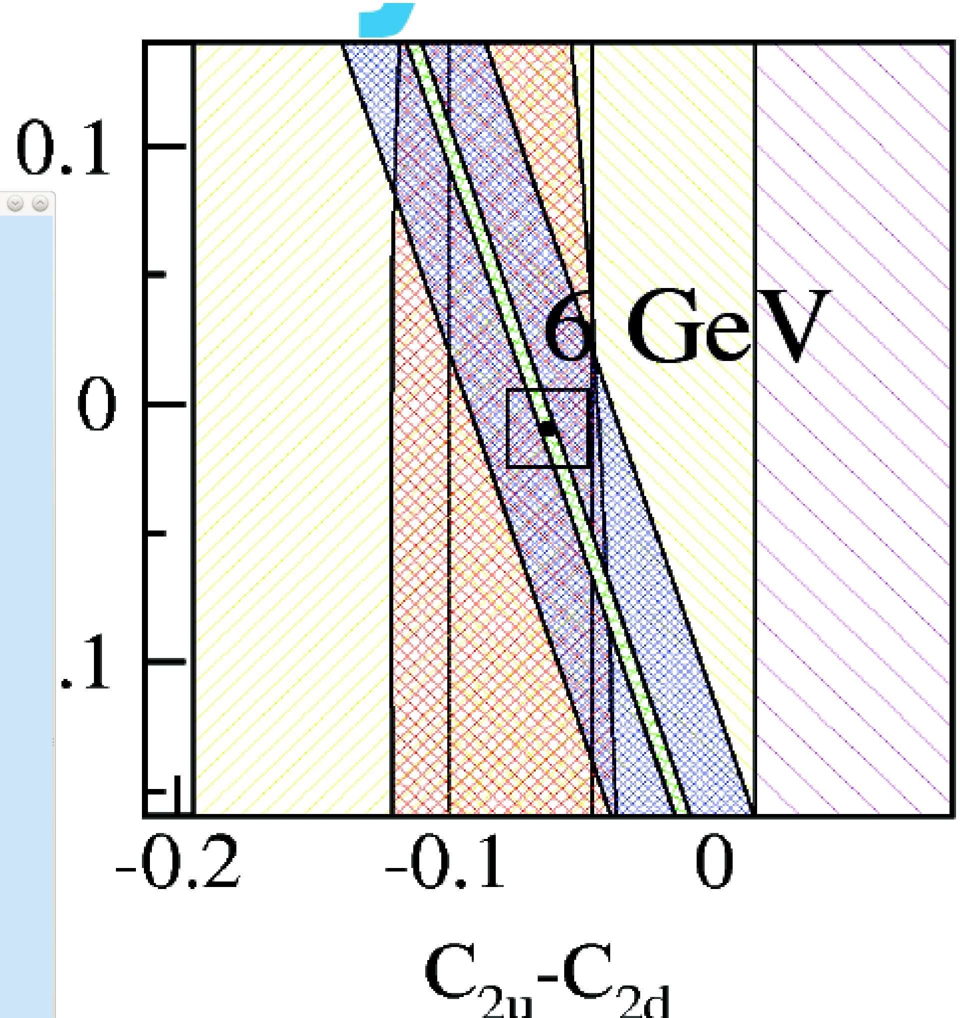
PVDIS @ JLab 6 GeV: potential to improve C_{2q} knowledge if hadronic effects are small.

Coherent PVDIS Program with SoLID @ 11 GeV

Fully approved, 180 days, rated A

A 20M$ device





Other PVDIS physics topics: $\sin\theta_W$, charge symmetry violation, diquarks, d/u of the proton (90 days);

Also Semi-inclusive DIS.

Thanks to Everyone Working (Worked) with Me

PVDIS analysis log #77

```
#input must be right in front of input
#preshower
1 preshower drift 3.0 xlow 0.0 xhigh 1.0 ylow 0.0 yhigh 1.0 output 0 10 1
2 preshower drift 3.0 xlow 1.0 xhigh 2.0 ylow 0.0 yhigh 1.0 output 0 10 1
3 preshower drift 3.0 xlow 2.0 xhigh 3.0 ylow 0.0 yhigh 1.0 output 0 10 1
4 preshower drift 3.0 xlow 3.0 xhigh 4.0 ylow 0.0 yhigh 1.0 output 0 10 1
5 preshower drift 3.0 xlow 4.0 xhigh 5.0 ylow 0.0 yhigh 1.0 output 0 10 1
6 preshower drift 3.0 xlow 5.0 xhigh 6.0 ylow 0.0 yhigh 1.0 output 0 10 1
7 preshower drift 3.0 xlow 6.0 xhigh 7.0 ylow 0.0 yhigh 1.0 output 0 10 1
8 preshower drift 3.0 xlow 7.0 xhigh 8.0 ylow 0.0 yhigh 1.0 output 0 10 1

#shower
101 shower drift 4.0 xlow 0.0 xhigh 1.0 ylow 0.0 yhigh 1.0 output 0 10 1
102 shower drift 4.0 xlow 1.0 xhigh 2.0 ylow 0.0 yhigh 1.0 output 0 10 1
103 shower drift 4.0 xlow 2.0 xhigh 3.0 ylow 0.0 yhigh 1.0 output 0 10 1
104 shower drift 4.0 xlow 3.0 xhigh 4.0 ylow 0.0 yhigh 1.0 output 0 10 1
105 shower drift 4.0 xlow 4.0 xhigh 5.0 ylow 0.0 yhigh 1.0 output 0 10 1
106 shower drift 4.0 xlow 5.0 xhigh 6.0 ylow 0.0 yhigh 1.0 output 0 10 1
107 shower drift 4.0 xlow 6.0 xhigh 7.0 ylow 0.0 yhigh 1.0 output 0 10 1
108 shower drift 4.0 xlow 7.0 xhigh 8.0 ylow 0.0 yhigh 1.0 output 0 10 1

#other modules
201 428F offset 0.0 input 0 209 0 1 210 0 output 0 16 1
202 706 threshold 100 width 20 input 0 201 0 output 0 4 1 1 4 1
203 706 threshold 100 width 100 input 0 202 0 output 0 4 1
204 758 mode and width 16 input 0 202 1 1 206 1 output 0 16 1
205 428F offset 0.0 input 0 210 1 output 0 16 1
206 706 threshold 50 width 20 input 0 205 0 output 0 4 1 1 4 1
207 706 threshold 50 width 100 input 0 206 0 output 0 4 1
208 758 mode and width 16 input 0 203 0 1 207 0 output 0 16 1
209 sum8 input 0 101 0 1 102 0 2 103 0 3 104 0 4 105 0 5 106 0 6 107 0 7 108 0 output 0 4 1
210 sum8 input 0 1 0 1 2 0 2 3 0 3 4 0 4 5 0 5 6 0 6 7 0 7 8 0 output 0 4 1
```

Students:

Huaibo Ding (THU, China)

Xiaoyan Deng (UVa)

Diancheng Wang (UVa)

Kai Pan (MIT)

Jie Liu (UVa)

Postdocs:

Ramesh Subedi

Zhiwen Zhao

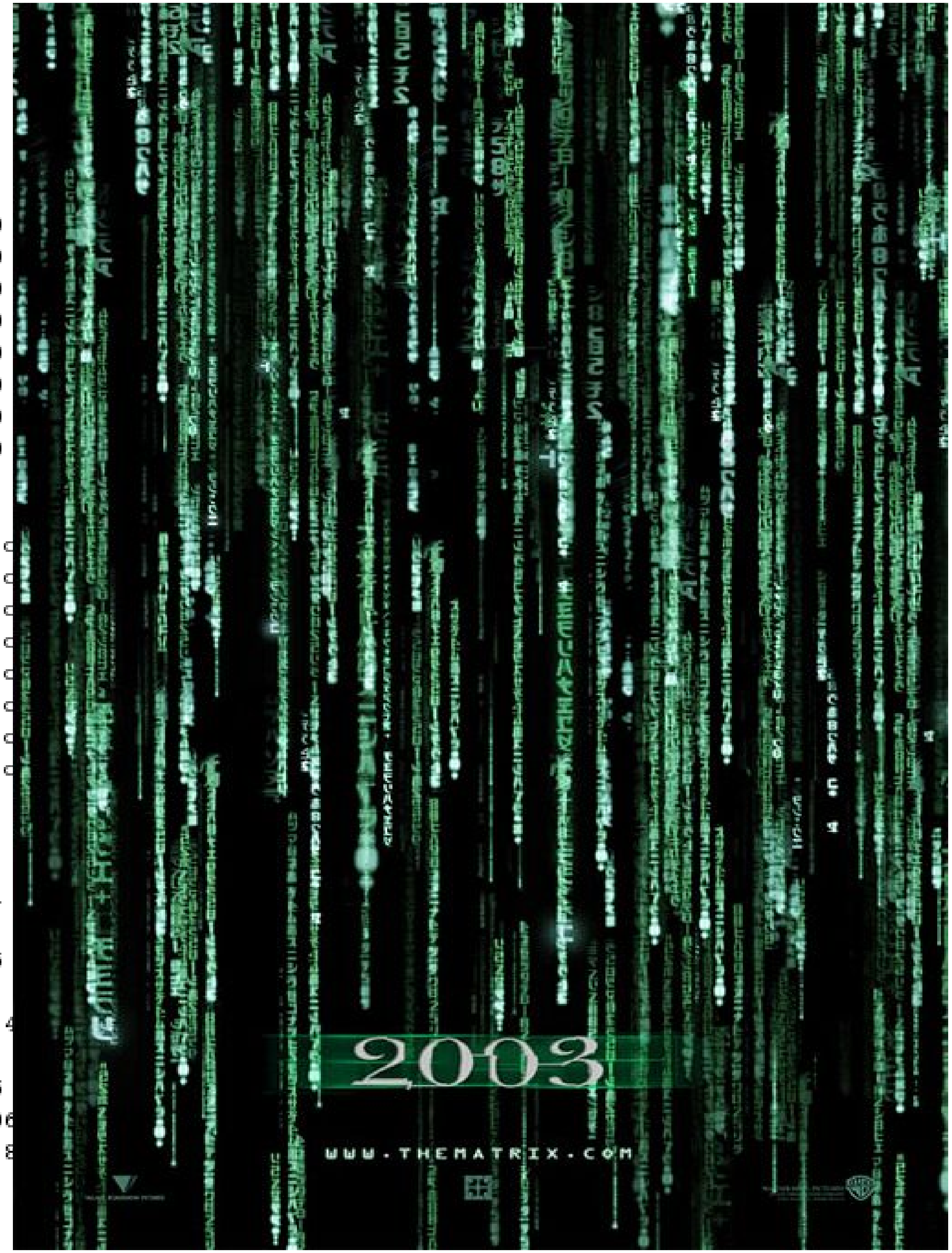
Thanks to Everyone Working (Worked) with Me

PVDIS analysis log #77

```
#input must be right in front of input
#preshower
1 preshower drift 3.0 xlow 0.0 xhigh 1.0 ylow 0.0 yhigh 1.0
2 preshower drift 3.0 xlow 1.0 xhigh 2.0 ylow 0.0 yhigh 1.0
3 preshower drift 3.0 xlow 2.0 xhigh 3.0 ylow 0.0 yhigh 1.0
4 preshower drift 3.0 xlow 3.0 xhigh 4.0 ylow 0.0 yhigh 1.0
5 preshower drift 3.0 xlow 4.0 xhigh 5.0 ylow 0.0 yhigh 1.0
6 preshower drift 3.0 xlow 5.0 xhigh 6.0 ylow 0.0 yhigh 1.0
7 preshower drift 3.0 xlow 6.0 xhigh 7.0 ylow 0.0 yhigh 1.0
8 preshower drift 3.0 xlow 7.0 xhigh 8.0 ylow 0.0 yhigh 1.0

#shower
101 shower drift 4.0 xlow 0.0 xhigh 1.0 ylow 0.0 yhigh 1.0 c
102 shower drift 4.0 xlow 1.0 xhigh 2.0 ylow 0.0 yhigh 1.0 c
103 shower drift 4.0 xlow 2.0 xhigh 3.0 ylow 0.0 yhigh 1.0 c
104 shower drift 4.0 xlow 3.0 xhigh 4.0 ylow 0.0 yhigh 1.0 c
105 shower drift 4.0 xlow 4.0 xhigh 5.0 ylow 0.0 yhigh 1.0 c
106 shower drift 4.0 xlow 5.0 xhigh 6.0 ylow 0.0 yhigh 1.0 c
107 shower drift 4.0 xlow 6.0 xhigh 7.0 ylow 0.0 yhigh 1.0 c
108 shower drift 4.0 xlow 7.0 xhigh 8.0 ylow 0.0 yhigh 1.0 c

#other modules
201 428F offset 0.0 input 0 209 0 1 210 0 output 0 16 1
202 706 threshold 100 width 20 input 0 201 0 output 0 4 1 1
203 706 threshold 100 width 100 input 0 202 0 output 0 4 1
204 758 mode and width 16 input 0 202 1 1 206 1 output 0 16
205 428F offset 0.0 input 0 210 1 output 0 16 1
206 706 threshold 50 width 20 input 0 205 0 output 0 4 1 1 4
207 706 threshold 50 width 100 input 0 206 0 output 0 4 1
208 758 mode and width 16 input 0 203 0 1 207 0 output 0 16
209 sum8 input 0 101 0 1 102 0 2 103 0 3 104 0 4 105 0 5 106
210 sum8 input 0 1 0 1 2 0 2 3 0 3 4 0 4 5 0 5 6 0 6 7 0 7 8
```



Summary

My involvement:

Sponsored by

NSF Nuclar Physics (2007-2009)

DoE Early Career (2010-2014)

- We have learned a lot from deep inelastic scattering experiments: how quarks and gluons share the energy of the nucleon
- And how quarks are polarized inside the nucleon:
  - The 6 GeV results from JLab showed the importance of the quark orbital motion ← (sole) PhD student, 2000-03
  - several 12 GeV measurements have been planned (flagship experiments of the 12 GeV Upgrade); ← spokesperson of 2 neutron experiments
- Parity Violation DIS experiments can access the quark neutral weak coupling + the structure of the nucleon beyond the simple parton model:
  - The 6 GeV PVDIS measurement at JLab was completed successfully in Dec 2009, data to be released before 2012; ← leading spokesperson, 2003-2005-2008-2009-present
  - The 12 GeV SoLID program is being planned. ← Core group, leading simulation and calorimeter R&D